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**AN ACTIVE LINER SYSTEM FOR JET ENGINE
EXHAUST SILENCERS
PHASE I**

**István L. Vér
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**BBN SYSTEMS AND TECHNOLOGIES
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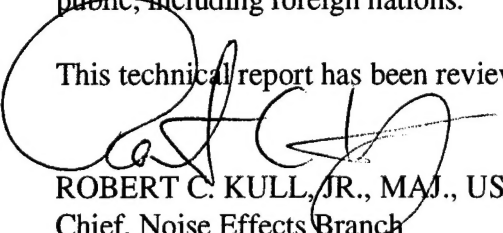
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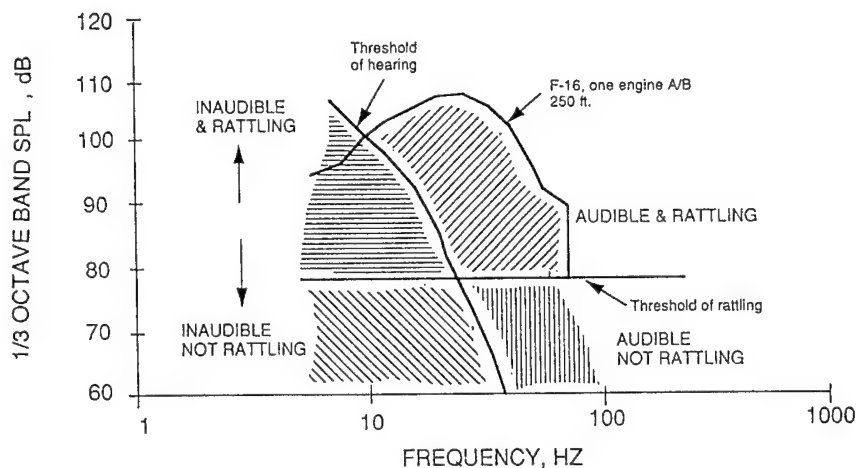
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EXECUTIVE SUMMARY

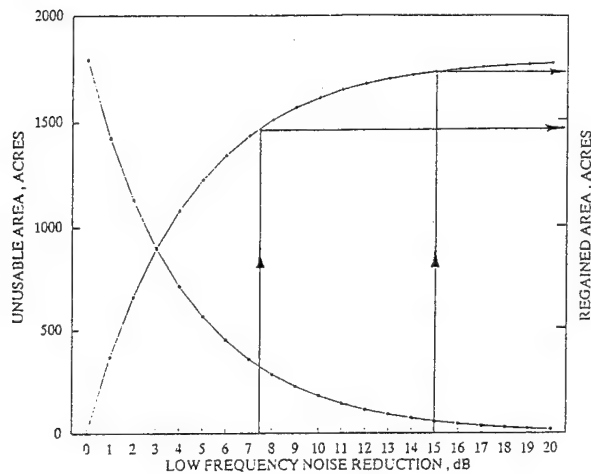
Afterburning jet engines represent the most powerful sources of noise produced by human civilization. To test these engines in and out of airframe, noise abated test facilities such as Hush Houses and Jet Engine Test Cells are utilized which reduce the mid and high frequency component of the jet noise to levels which are safe for human exposure. However, these traditional passive silencers provide practically no sound attenuation at low frequencies (8Hz to 80Hz). Consequently, only the unattenuated low frequency noise emanating from these noise abated test facilities is a serious problem which is likely to increase with the introduction of more powerful jet engines.

When sound propagation conditions are favorable, low frequency noise (even if it is below the threshold of hearing) can rattle lightweight building components such as windows, doors, plaster walls, up to miles away from the test facility. Rattling, which has been connected with earthquakes in the human experience, inevitably evokes intense fear and instant complaints. As shown in the diagram below, the low frequency noise levels at 250 ft from an Air Force Hush House may be 106 dB which is 26 dB above the 80 dB threshold of rattling. To avoid rattling, lightweight buildings would need to be placed no less than 5000 ft from the Hush House.



Human Perception of Low Frequency Noise

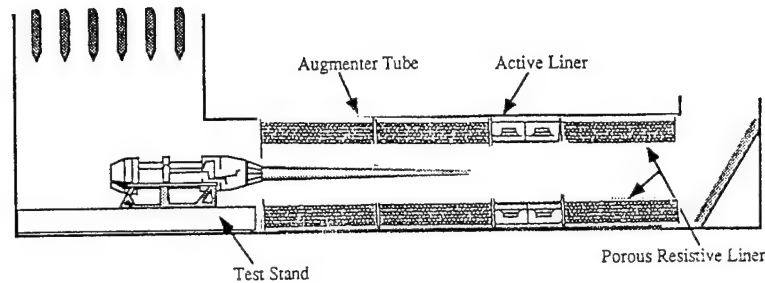
As shown in the second diagram below, in this specific case, it results in a loss of 1800 acres of highly valuable land around the test facility for construction of lightweight buildings. Obtaining a 7.5 dB reduction of the low frequency noise output would regain 1400 acres (78%) and a 15 dB reduction would regain 96% of the land around the test facility for unrestricted use.



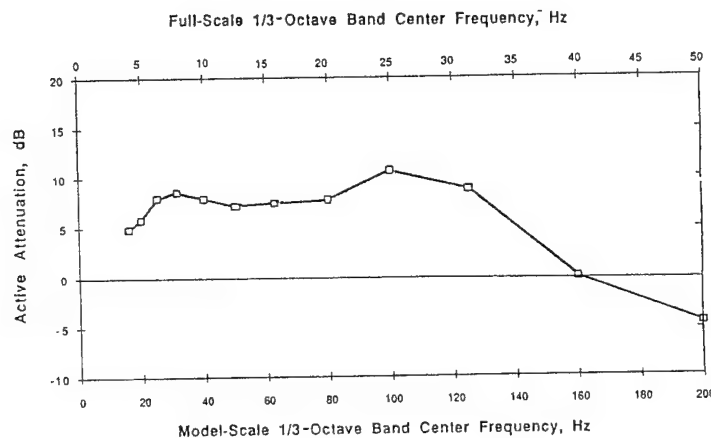
Economic Implications of Low Frequency Noise Reduction

In the framework of the U.S. Air Force's Advanced Technology Active Noise Reduction Initiative, BBN Systems and Technologies (BBN) has been tasked to carry out an experimental program to evaluate the feasibility of a new BBN-proposed concept of an Active Liner to obtain substantial reduction of the low frequency exhaust noise of jet engine test cells and hush houses.

Using a 1:4 scale model of a jet engine test augments, BBN has demonstrated experimentally the feasibility of obtaining 8 to 15 dB reduction of the low-frequency noise by inserting one or two active liner sections into a typical jet engine test cell augments. The arrangement of the active and passive sections is shown in the third sketch. The active attenuation obtained by inserting a single active section between passive sections is documented in the last graph.



Active Exhaust Silencer Concept



Measured Attenuation for One Active Section

The results of BBN's Phase I investigation, documented in this report, has proven that the new concept of the active liner is a feasible way to obtain substantial dissipative attenuation at low frequencies where traditional passive silencers are ineffective.

This report is divided into eight sections. Section 1 describes the background and scope, elaborates the problems caused by low frequency noise, and deals with its land use implications. Section 2 contains a description of the active liner concept. Section 3 deals with control strategies. Section 4 contains a description of the model-scale augmenter including the passive and the active section and the feedback control system. Experimental results are reported in Section 5. Section 6 deals with full-scale ramifications and Section 7 with risk assessment. Section 8 contains a summary of key findings.

1 INTRODUCTION

This section contains information about:

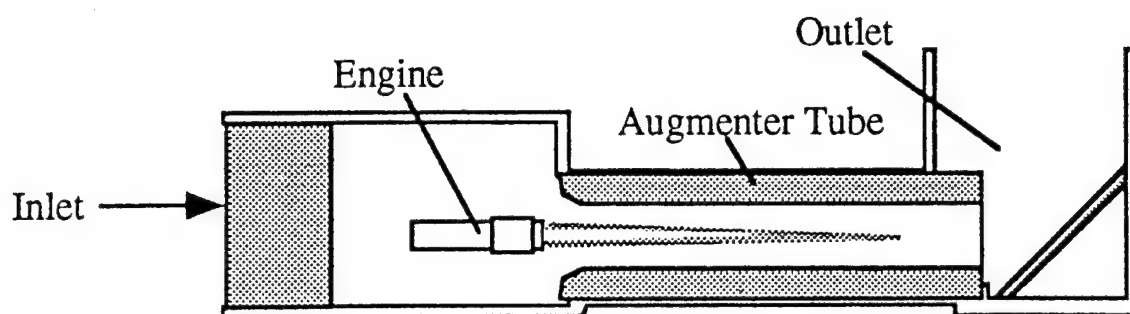
1. The background of this project
2. Typical passive exhaust silencers and the reasons why they provide practically no attenuation of the low frequency components of jet noise
3. Problems caused by the low frequency noise
4. Land use implications of low frequency noise, and
5. Scope of Phase I work

1.1 Background

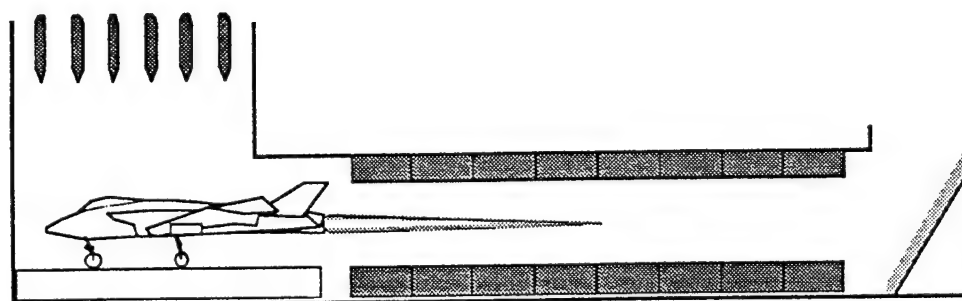
Hush houses and jet engine test cells are designed to yield a substantial reduction of the A-weighted sound pressure level. Jet engine test cells, such as depicted in Fig 1A, are used exclusively for out-of-airframe testing of engines. Hush houses, shown in Fig 1B, are primarily used for ground runup of different types of aircraft (i.e. in-airframe testing of the engine) and may also be used for out-of-airframe testing of engines. Both facilities have one (primary) or two (primary and secondary) air inlet silencers and a lined augments tube that serves as an exhaust silencer. Fig 2 shows a plan view of a typical Type T-10 Air Force hush house. Air Force jet engine test cells utilize the same exhaust silencing system as the hush house.

The air inlet silencers are parallel baffle type which provide efficient sound attenuation for engine inlet noise which is of predominantly high frequency. However, parallel baffle silencers are nearly transparent for low frequency noise. Therefore, it is essential to avoid low frequency exhaust noise control measures which result in directing of the low frequency noise toward the inlet silencer, such as "corebusters" or traditional active noise control that merely reflects low frequency sound from the augments toward the inlet, where it will pass through the inlet silencer unattenuated. In the process of passing through the test section, the low frequency noise exposes the aircraft or engine to substantially higher levels than they experience during unabated ground runup or in flight. The increased noise exposure will result in increased sound-induced vibration and stress of aircraft or engine components.

In modern air-cooled test facilities the lined augments tube, which provides attenuation for the jet exhaust noise, is 60 ft to 90 ft long. As shown schematically in Fig 3, the exhaust noise is generated in an extended region where the hot, high velocity jet mixes with the surrounding cool air. High frequency noise is generated near to the jet exhaust plane where eddy size is small, and low frequency noise is generated at the downstream end of the mixing region where eddies are larger. Consequently, it is important to locate the active



(a) Jet Engine Test Cell



(b) Hush House

Fig. 1 Conceptual Sketch Noise Abated Ground Runup

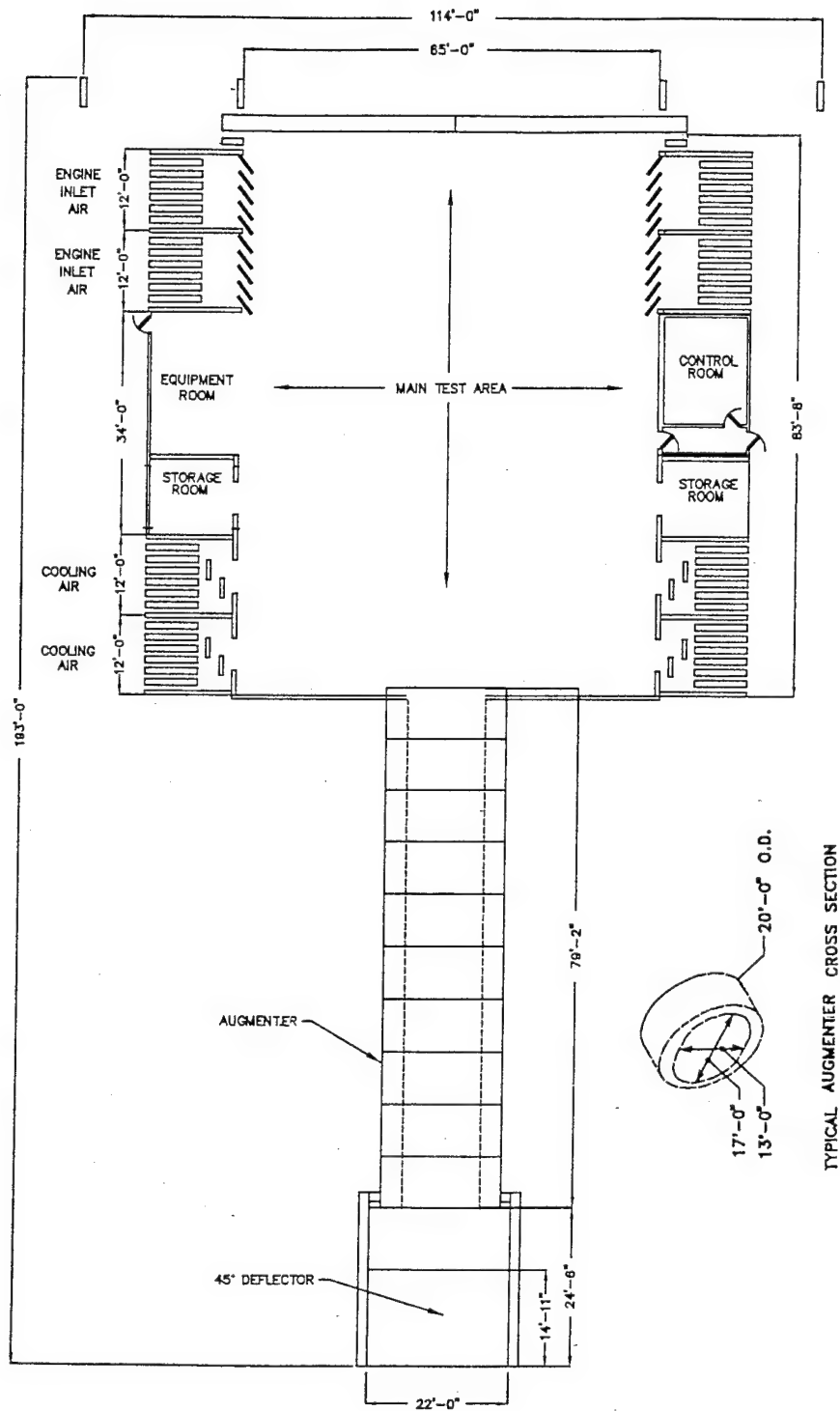


Fig. 2 Plan View of a Typical Type T-10 Air Force Hush House

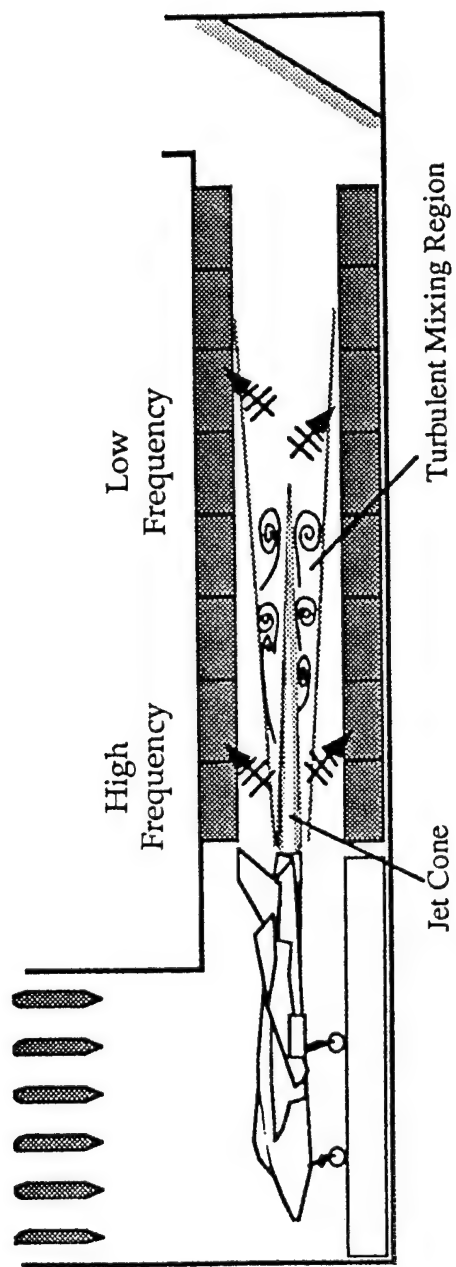


Fig. 3 Distribution of Sound Sources in the Turbulent Mixing Region in Jet Exhaust

low frequency silencer section near to the downstream end of the augmentor tube beyond the location of low frequency sound sources, which are of the order of 60 ft from the augmentor entrance for contemporary aircraft.

1.2 Typical Passive Lined Augmenters

The two typical lined augmentor configurations used with jet engine test cells and hush houses are shown in Fig 4. Sketch A shows the homogeneous porous liner configuration generally used in the U.S. Air Force's test facilities. The lining thickness may vary from 1 to several feet. The lining material is usually basalt wood or glass fiber. Sketch B in Fig 4 depicts a liner that consist of a thin (2 in to 4 in) fibrous sound absorbing material with a much thicker partitioned airspace behind. The fibrous sound absorbing material is the same as for the homogeneous liner. This augmentor acoustic treatment is generally found in test facilities of the U.S. Navy.

Figures 5A and 5B show predicted plane wave sound attenuation of a 10 ft long, 10 ft inside diameter and 18 ft outside diameter augmentor tube section of the construction depicted in Figs 4A and 4B respectively. Note that the sound attenuation below 10 Hz is between 1 dB and 2 dB. The reason for the lack of low frequency performance, as discussed in detail in Ref 1, is the stiffness of the air in the liner volume. In fact, noise abatement specifications were only provided for the Air Force hush house design at frequencies from the 63 Hz center frequency octave band and higher.

Because passive liners provide good mid and high frequency sound attenuation but hardly any low frequency sound attenuation, the noise emanating from traditional noise abated test facilities has a spectrum where the overall sound pressure is dominated by low frequencies.

1.3 Problems Caused by Low Frequency Noise

Usually the acoustic performance specification given to hush house designers is an 85 dBA limit at 250 ft. This criterion, along with two measured spectra are shown in Fig 6. The spectra are below the criterion curve by more than 10 dB at high frequencies and meet it at low frequencies. Accordingly, one can be confident that hush house noise control is not a high frequency problem. The problem is the high level (over 100 dB) of the very low frequency component of the exhaust noise.

The practically unattenuated low frequency noise emanating from hush houses and jet engine test cells causes serious problems as explained by considering a case history of a BBN project [2]. At Luke Air Force Base in Phoenix, Arizona, the low frequency exhaust noise of the hush house during afterburner (A/B) runup of the F-16 aircraft and during the out-of-airframe run of the F100-PW-100 engine

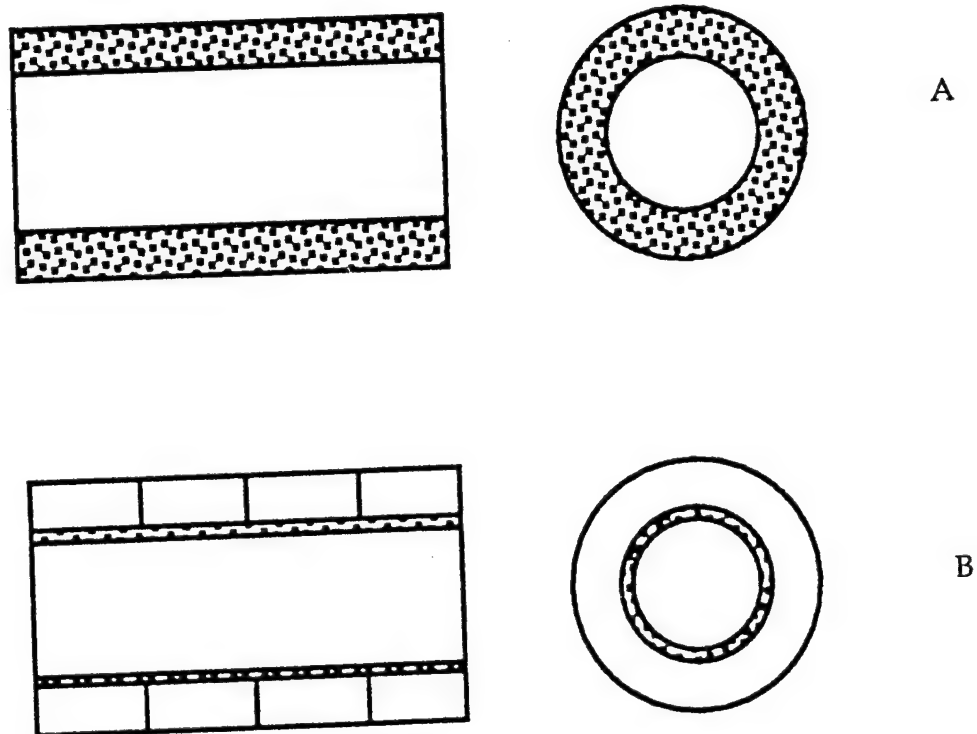


Fig. 4 Typical Lined Augmenter Configurations
A. Thick Homogeneous Liner
B. Thin Porous Layer with Airspace Behind

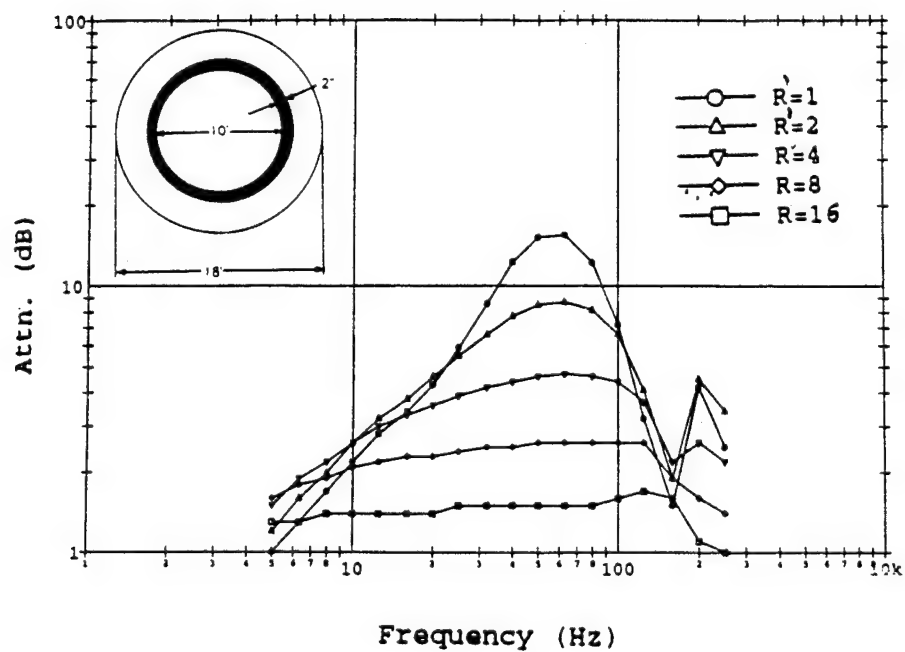
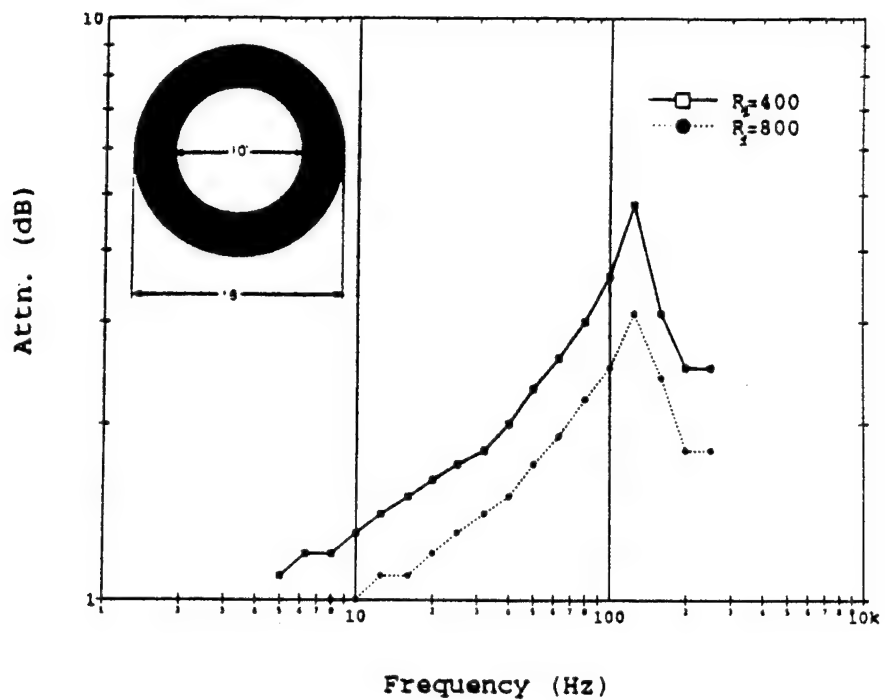


Fig. 5 Computed Sound Attenuation of a 10 ft Long,
10 ft Inside Diameter Augmenter Section

- A.** Homogeneous Liner; Flow Resistivity R_1 [Nsec/m³]
- B.** Thin Porous Layer with Airspace Behind Flow Resistance R in ρc Units

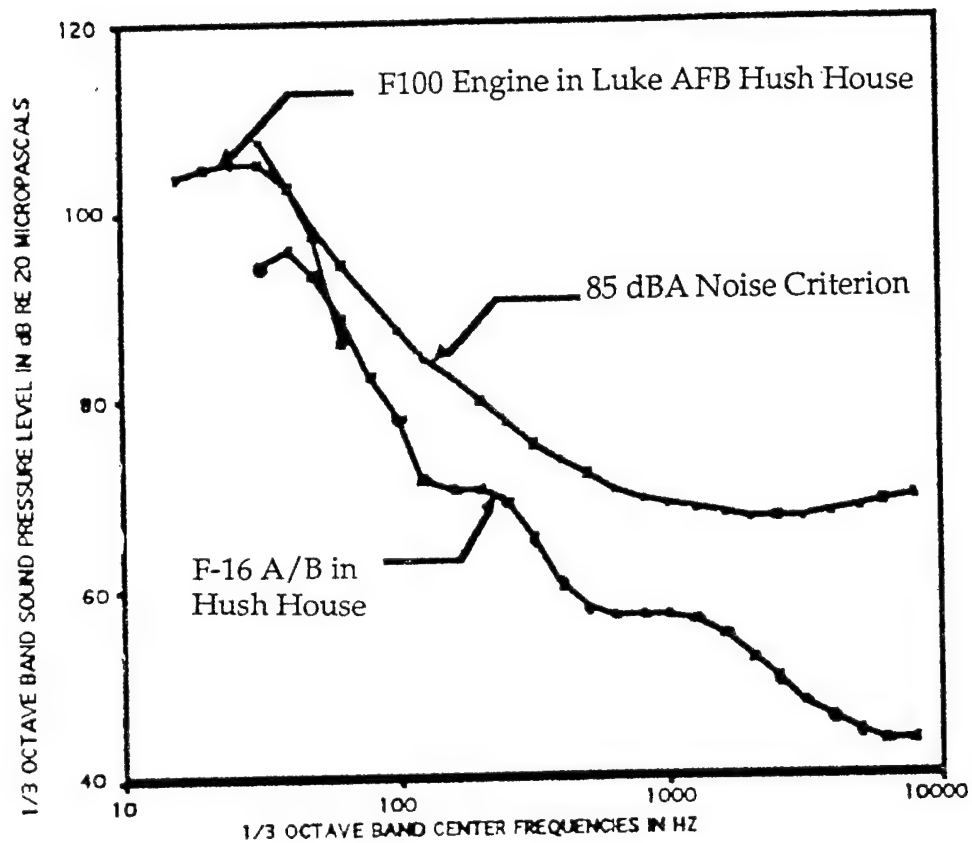


Fig. 6 Two Measured Spectra at 250 ft from a Typical Hush House; the 85 dBA Noise Criteria Curve is Shown for Comparison

vibrated the walls of a lightweight building located 900 ft from the hush house. The sound-induced building vibration was severe enough to rattle pictures on the wall and cause complaints of headaches and fatigue.

The relationship between low frequency noise and sound-induced rattling is illustrated in Fig 7 which shows 1/3-octave band spectrum of the low frequency noise measured at 250 ft from a typical Air Force hush house with the F-16 aircraft operating in A/B, the threshold of human hearing and the approximate threshold of rattling of lightweight buildings.

If the level of the low frequency noise is above both the threshold of hearing and the threshold of rattling, a human observer perceives both the noise and the rattling. If the level is above the threshold of rattling but below the threshold of hearing, the human observer does not hear the low frequency noise directly but perceives its secondary effect the rattling of windows, doors, etc. The perception is a combination of sensing the sound-induced vibration and hearing the secondary noise produced by the rattling. This combination of sensations has been connected with earthquakes in human experience and may evoke fear and vigorous complaints. Once the level of the low frequency noise falls below the threshold of rattling, but is still above the threshold of hearing, the faintly perceived low frequency noise is usually not a cause of complaints. Finally, if the level falls below both the threshold of hearing and the threshold of rattling the low frequency noise is not perceived even under the most quiet ambient noise conditions.

1.4 Land Use Implications of Low Frequency Noise

To avoid rattling of lightweight buildings caused by low frequency noise emission of jet engine test cells and hush houses, it is necessary to locate such buildings far enough away so that the level of the low frequency noise falls below 80 dB.

Referring back to Fig 7, the closest distance for locating a lightweight building would be 5000 ft.* As noise levels are reduced, it is possible to locate structures closer to the hush house. Fig 8 shows, for this typical case, the relationship between the land area lost or that recovered for unrestricted use and the noise reduction achieved. The curve has a pronounced "knee" and soon reaches a point of diminishing returns. A decrease of 7.5 dB of the low frequency noise emission would result in regaining 78% (1500 acres) and a 15 dB reduction in regaining 96% (1750 acres) of the land around the test facility for unrestricted use.

* $r = 250 \times 10^{26/20} = 5000 \text{ ft}$

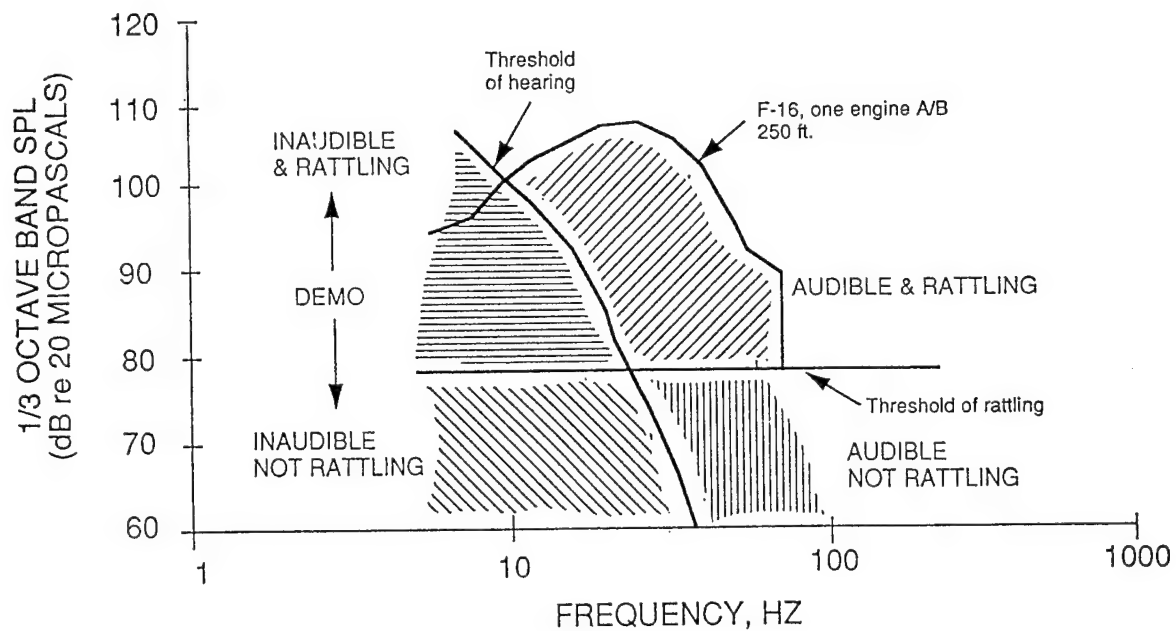


Fig. 7 Human Perception of Low Frequency Noise

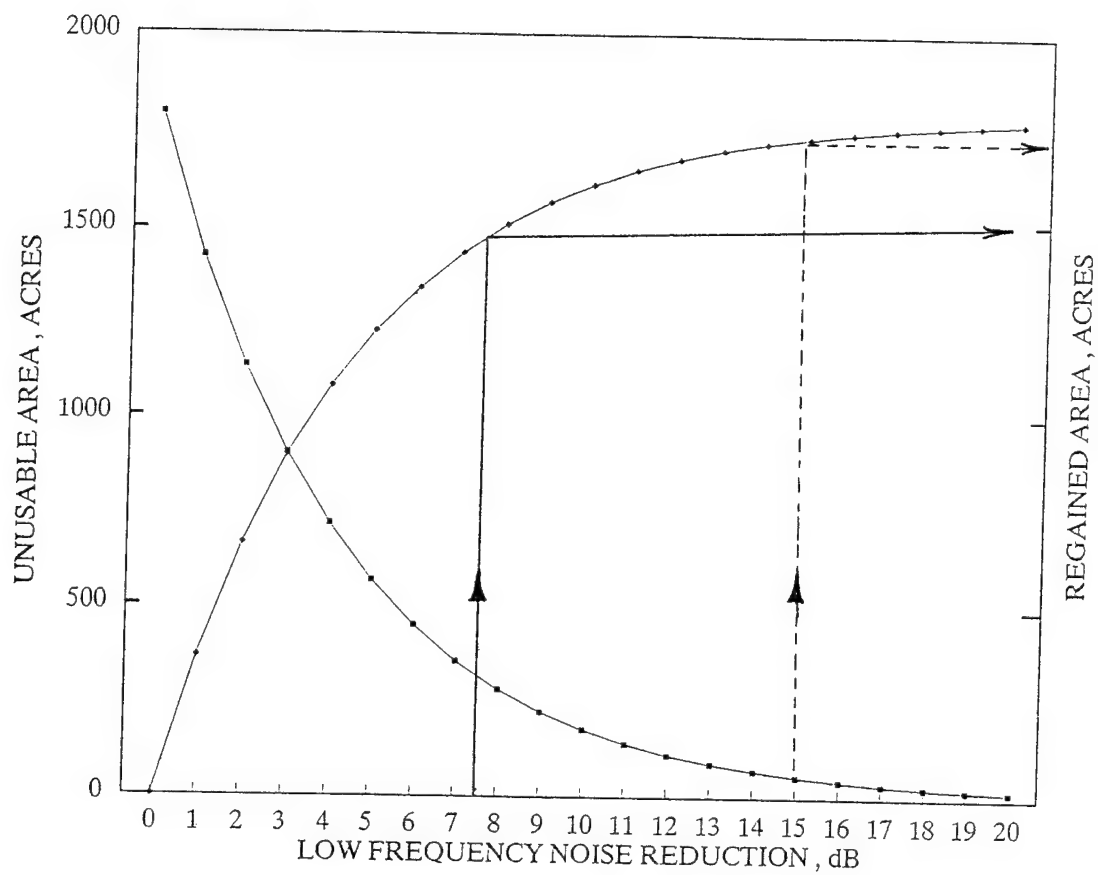


Fig. 8. Land Area Regained by Reducing Low Frequency Exhaust Noise Emissions

Considering that the land around such facilities is usually connected to roads and utilities, the gained real estate is highly valuable. Assuming the cost of land at \$2000/acre at unrestricted use and that the restricted use reduces this by 50 %, the 7.5 dB and 15 dB low frequency noise reduction would increase land values around our typical hush house or jet engine test cell by \$1.5 million and \$1.75 million respectively. In the current climate of base closures, this land may become even more valuable as more and more facilities are moved onto fewer and fewer bases. Consequently, funds invested in developing and implementing low frequency noise control measures are likely to result in substantial savings to the U.S. Air Force in terms of land required for jet engine testing facilities.

Since passive noise control measures are ineffective in producing low frequency noise reduction, the current practice is to design aircraft and engine ground runup facilities to meet 85 dBA noise criteria at 250 ft without limiting the low frequency noise emission. This shortcoming in the acoustical performance specifications may lead to situations (such as at Luke and Langley Air Force Bases) where the test facility meets the 85 dBA noise criteria but the unattenuated low frequency noise causes rattling of lightweight structures and results in vigorous complaints, sometimes as far a distance as 1.8 miles.

The active noise control concept described in this report is a much needed new measure that promises to achieve substantial reduction of the low frequency noise emission of aircraft and engine ground runup facilities.

1.5 Scope of Phase I Work

BBN Systems and Technologies (BBN) has proposed a new proprietary concept of an "Active Liner" that yields an exceptionally high rate of attenuation of the low frequency noise propagating in the augmentor tube (Ref. 1). The U.S. Air Force, in the framework of its Advanced Technology Active Noise Reduction Initiative, tasked BBN to demonstrate experimentally the feasibility of the active liner concept to reduce substantially the low frequency components of noise emanating from the exhaust of jet engine test cells and hush houses. The experimental work was carried out on a 1:4 scale model augmentor tube utilizing high power loudspeakers as a noise source. Temperature and turbulence effects were not modeled during this first phase of the project.

2 ACTIVE LINER CONCEPT

This section contains information about the principle of operation of the Active Liner, its preferable location within the augmenter tube, and its advantages.

2.1 Principle of Operation

Current passive exhaust silencers are deficient at low frequencies, where the input impedance of a practically sized liner becomes so large that it impedes acoustic flow into the liner. The active liner, shown in a partial cross-section in Fig 9, directly addresses this deficiency by actively reducing the stiffness impedance of the front cavity between the liner and actuators, thereby enabling the absorptive liner to be effective even at very low frequencies. This active control scheme may be viewed as actively increasing the compliance or effective volume of the enclosed air chamber backing the porous resistive liner.

The acoustic impedance of the front cavity is reduced by driving the actuators within each segment so as to reduce the sound pressure in the front cavity toward zero. When a positive acoustic pressure disturbance reaches the passage side of the liner, air flows from the passage into the forward cavity. This starts to raise the pressure in the cavity and this increase is sensed by the microphone. The microphone signal is processed by the controller which sends a command voltage to the power amplifier. The amplifier applies a proportional voltage to the loudspeaker coil. An electrical current flows through the speaker coil which is embedded in a magnet. As a result, a force is generated on the coil which drives it and the attached speaker diaphragm away from the liner, thereby keeping the pressure in the forward cavity from rising. If the acoustic pressure in the augmenter tube passage were negative, just the opposite process would occur to keep the pressure in the forward cavity from dropping too much.

The sensor microphones, the controller, the actuators -- together with the thin porous liner -- constitute the active liner. As discussed later, the control system may be Single Input-Single output (SISO) or Multiple Input-Multiple Output (MIMO) variety.

2.2 Preferable Location of Active Segments

Figure 10 shows the preferred location of active liner segments in a typical augmenter tube silencer. The active segments should be near to the downstream end of the augmenter tube where the low frequency noise generation of the jet mixing process is already completed. The top sketch in Fig 10 depicts an active section containing two active segments without separation and the bottom sketch two active sections separated by a passive section. Separating the active sections by passive sections reduces the cross-coupling between the active segments, which results in improved active attenuation performance.

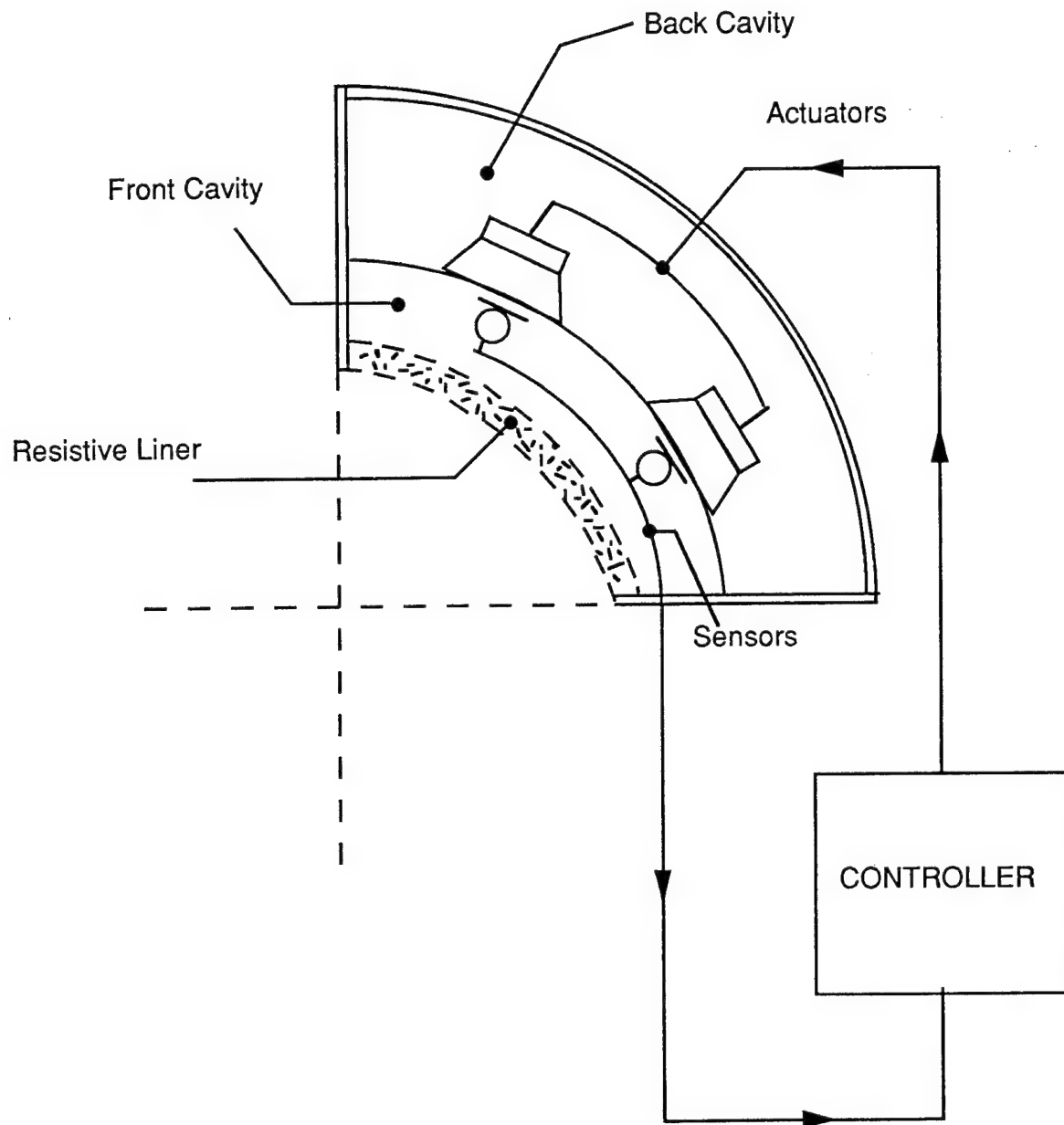


Fig. 9 Sketch of a Single Cell of an Active Augmenter Liner Segment

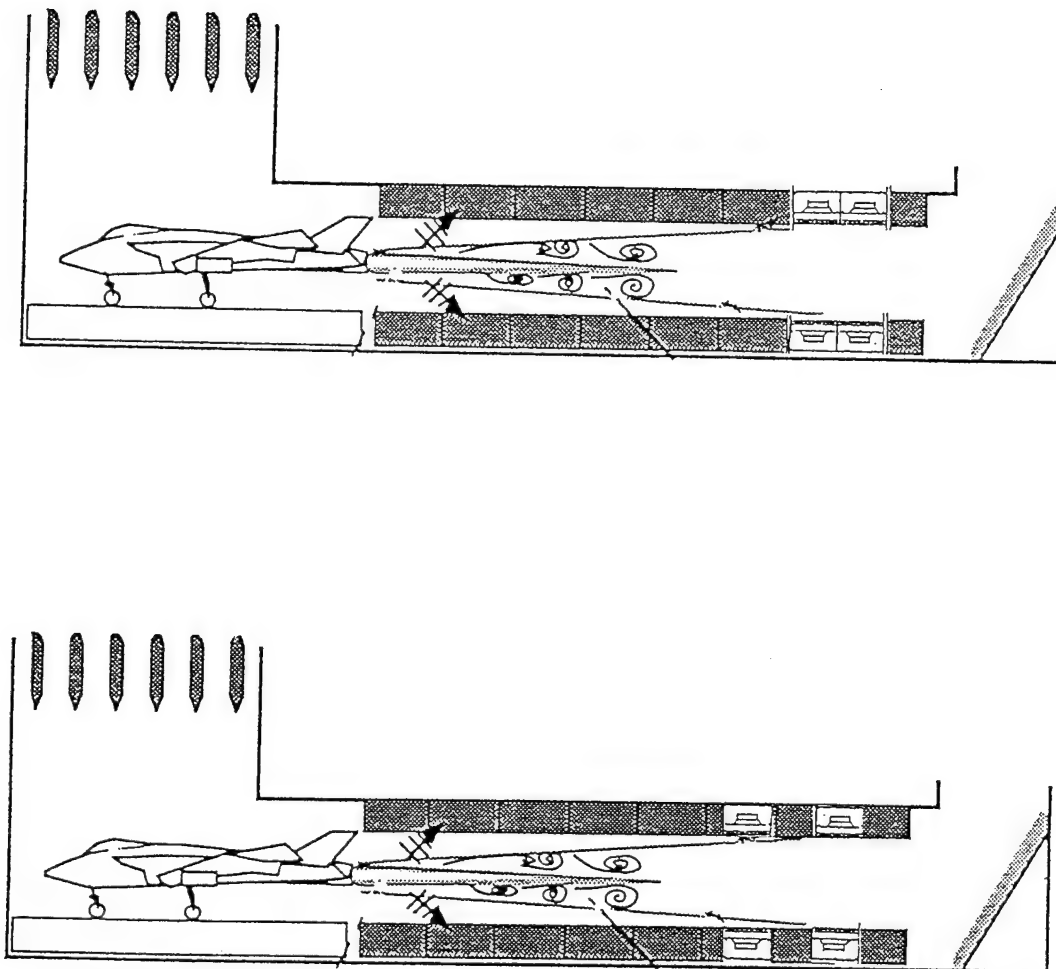


Fig. 10 Preferred Location of Active Augmenter Liner Segments
Top: Single Active Segment
Bottom: Multiple Active Segments Separated by Passive Segments

2.3 Beneficial Features of the Active Liner

Our active liner has many advantages which are listed in Table 1. One of the major advantages is the multiple beneficial use of the porous sound absorbing layer which:

1. provides heat insulation between the augments tube passage and the front cavity;
2. filters out turbulent boundary layer pressure fluctuations;
3. works as an effective acoustical liner at mid and high frequencies which are beyond the range of the active control;
4. provides a highly damped acoustical cavity yielding a smooth, simple transfer function between the loudspeakers and the sensing microphone resulting in a stable and robust control system; and most important
5. dissipates (transforms into heat) the low frequency sound energy propagating in the duct.

Of course, the major advantage is that the active liner provides substantial dissipative attenuation of the low frequency noise which can not be obtained by passive means.

TABLE 1 ADVANTAGES OF THE ACTIVE LINER

Advantage	Why an Advantage
Control system is located entirely behind the liner.	Liner protects control system from high temperatures and turbulent flow within augments tube. Signal to noise of turbulent flow to acoustic pressure is very low making the measurement of transfer functions quick and easy.
Total liner attenuation is a function of active liner surface area.	The cost of the active liner is proportional to required noise attenuation for a particular installation. More attenuation can be added if requirements change.
The active liner concept is independent of a particular augments tube design.	Only modest engineering is required to backfit a traditional passive augments tube with an active liner, thereby reducing installation cost.
The space being controlled has simple acoustic characteristics.	No need for complex and expensive signal processing. Transfer functions can be quickly and easily measured making adaptation to changing temperatures and flows very quick.
The concept is very forgiving.	The goal is to introduce a large pressure gradient across the liner and most of the active attenuation is from the first 90 percent reduction of the sound pressure behind the liner. Absolute zero sound pressure is not needed at every location.
The active liner concept mostly absorbs acoustic energy	Conventional active control reflects a large percentage of the acoustic energy due to an impedance discontinuity between the passive and active sections. The active lining has the benefit of dissipating the sound energy.

3 ACTIVE LINER CONTROL STRATEGIES

Several options exist for the design of a control system which will reduce the acoustic pressure at the inner surface of the thin dissipative layer. Regardless of the specific algorithm or hardware used, each design must result in an actuator displacement such that the pressure at the inner surface of the porous layer is greatly reduced. The various control options have common components including microphones to sense the sound to be controlled, controller electronics to produce an actuator drive signal based on the sensor input, an actuator, and possibly a residual sensor to evaluate/verify the performance of the controller output.

Feedback and feedforward control are the two basic strategies available for use on the active silencer. In a feedback design the noise is immediately canceled upon sensing a change in the pressure. The feedforward design utilizes an upstream reference sensor to provide an advanced replica of the noise to be controlled. These two control designs are illustrated in Fig 11. The controller hardware can be composed of analog and/or digital components. Also, each algorithm can be implemented in a single-input-single-output (SISO) or multiple-input-multiple-output (MIMO) configuration.

The control configuration used for the scale model evaluations was a SISO feedback controller implemented using analog circuit boards. The scale model control design will be explained in more detail in Section 4.2.

3.1 Feedback Control

A feedback control implementation for the active silencer uses a microphone placed in the cavity between the liner and loudspeaker. It provides the input to the controller as shown in the top sketch of Fig 11. The control system reacts to a change in the pressure to maintain a reduced pressure at the inner surface of the porous layer. To do this the control system must have a near instantaneous response to changes in the dynamic pressure over a selected frequency range.

As shown in Fig 12, the feedback controller is composed of two parts, the compensation filter, G , and the regulation filter, H . The compensation filter is approximately the inverse of the plant transfer function, P , where the plant is the transfer function between the output voltage of the controller and the input voltage from the microphone. The plant includes characteristics of the loudspeaker, microphone, and acoustics of the space between the loudspeaker and liner.

The attenuation provided by the control system is the ratio of the open loop uncontrolled sound pressure to the closed loop controlled sound pressure as symbolized by T in Fig. 12. A typical attenuation curve is shown in Fig 13.

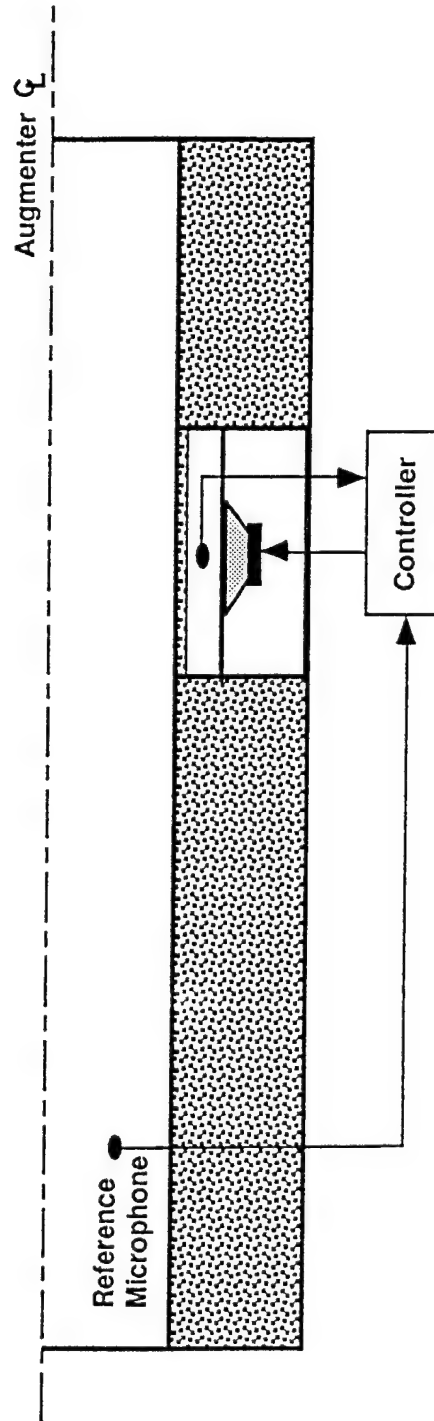
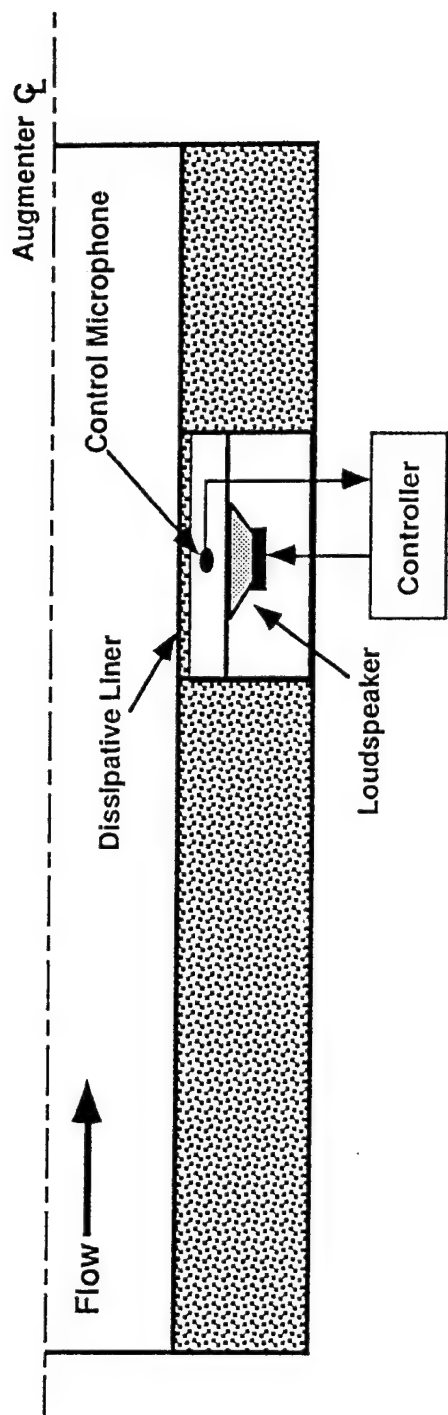


Fig. 11 Control Strategies for the Active Liner
 Top: Feedback Control
 Bottom: Feedforward Control

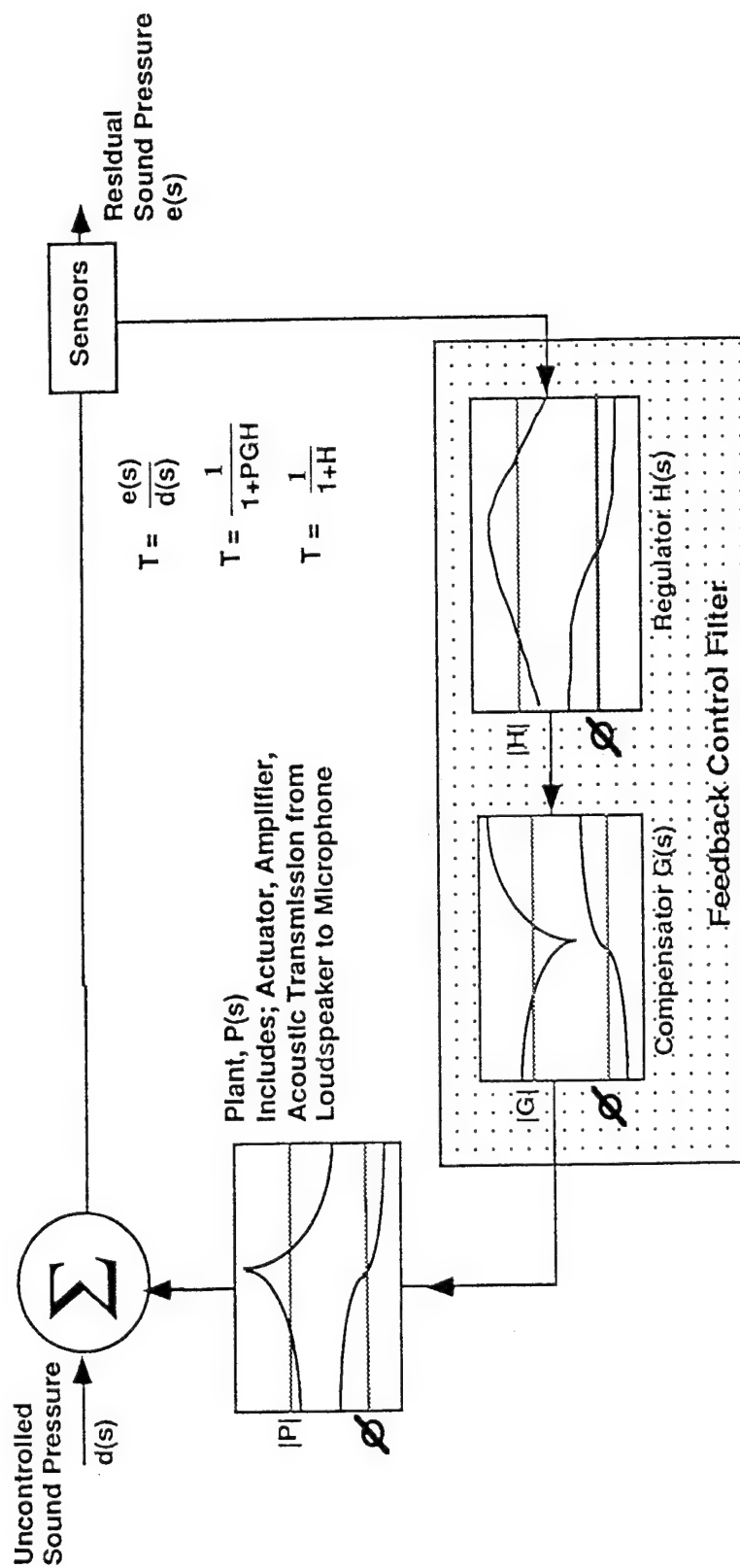


Fig. 12 Block Diagram of Feedback Control

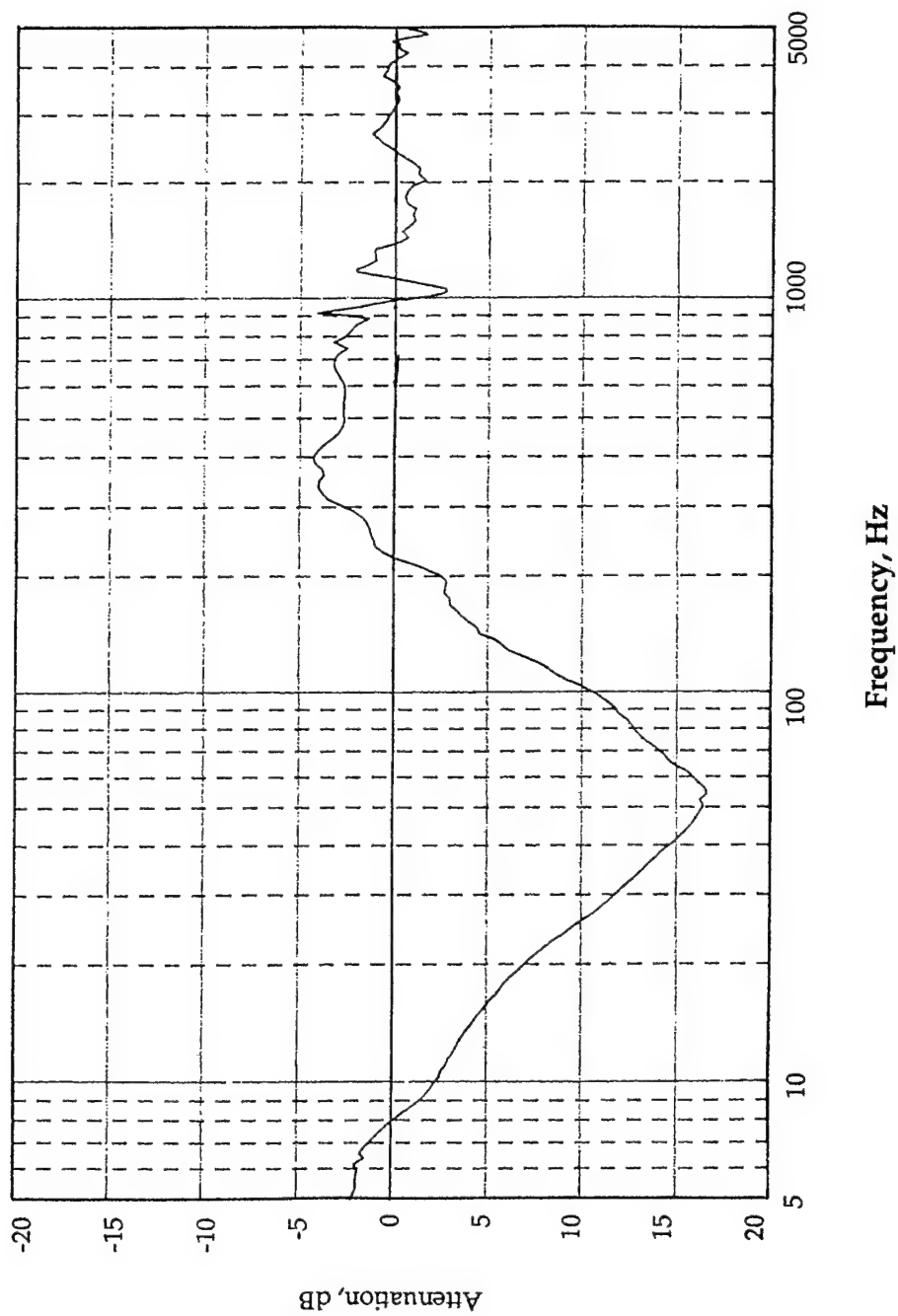


Fig. 13 Typical Attenuation vs. Frequency Curve
Provided by the Feedback Control System

Assuming that over the frequency range of interest the compensation is the inverse of the plant then the overall attenuation is defined by the regulation filter alone. The regulation filter is designed to have high gain over the regulation frequency range and attenuation outside the regulation frequency band where the compensation poorly approximates the plant.

3.2 Feedforward Control

The basic concept of a feedforward control design for the augments is to use an upstream reference microphone which feeds a predictive measurement of the propagating noise forward to the controller. If the reference microphone can provide a stable measurement of the propagating noise with a good signal to noise ratio then this signal can be used to provide additional time for calculating an output signal to cancel the noise as it reaches the active section. However, it is important that the signal to noise ratio at the reference microphone be high and that the transfer function between the noise measured at the reference sensor and the noise measured at the active section be stable. The reference microphone must be sensitive only to the propagating noise and not the convected turbulent boundary pressure fluctuations. Also, if the reference microphone is sensitive to the noise generated by the control actuator then this effect must be accounted for in the control design.

In the bottom sketch of Fig 11, the reference microphone placed upstream of the active section provides a prediction of the approaching plane wave sound. The signal from this reference microphone is used to calculate an appropriate output signal to cancel the sound pressure in the cavity behind the porous layer. The control microphone shown in the figure is used to continuously adapt the controller to changes in the plant. The ability to adapt requires implementation on digital hardware.

3.3 SISO and MIMO Control

As implied by the name, a single-input-single-output (SISO) control system measures the input from a single signal and calculates a single output signal. The single input can be from a single microphone or from the average of a microphone array. The single output may serve a single loudspeaker or a group of many loudspeakers. A multiple-input-multiple-output configuration takes in multiple signals and calculates the output for multiple loudspeakers. The effect of each loudspeaker on each microphone is accounted for in a MIMO configuration. If the effect of the cross coupling between the various loudspeakers and microphones becomes significant, then control instabilities can result unless the coupling is accounted for in the control design. The coupling effect can be accounted for by either using a spatial average of multiple microphones with a SISO controller or using a MIMO controller.

3.4 Analog and Digital Hardware

Whether the controller uses analog or digital hardware, the input and output signals are basically the same. However, internally they are manipulated quite differently. Because digital systems are processor based they have the advantage that they can be programmed to be self modifying, adaptive to changes in the response of the plant being controlled. A digital system can also control very complex systems requiring complicated filter shapes or multiple-input-multiple-output designs. However, there is a cost associated with the power of a digital system. Costs of digital hardware can be as much as an order of magnitude greater than that for an analog system and may also require significant software development.

In general if the plant transfer functions are relatively simple, and have limited temporal variation, then an analog implementation would be appropriate. However, for complex or time varying systems a digital controller would be required.

3.5 Selection of Control Strategy

Each of the various control strategy options has an appropriate use depending on the characteristics of the noise and space being controlled. The scale model control system used a SISO feedback control design implemented on an analog circuit board. This strategy was selected for several reasons. First, a feedback control system does not require an upstream microphone, therefore the entire control is localized behind the liner. The localized control results in relatively simple acoustic characteristic of the space between the loudspeaker and liner, as well as, in protection of sensors and actuators from high temperature and turbulent pressure fluctuations.

Because the acoustic characteristics of the space between the loudspeakers and liner was relatively simple analog hardware could be used to implement the control filters. The use of an analog control was considered to be more cost effective than a digital implementation.

4 MODEL-SCALE AUGMENTER WITH ACTIVE LINER

This section contains a description of the 1:4 scale model augmenter tube including the passive and active sections and that of the Single-Input Single-Output (SISO) feedback control system utilized in the active liner section.

4.1 Model Description

Figure 14 shows the 1:4-scale model augmenter assembly. It consists of three round passive sections and a round active section. Fig 15 depicts the construction of a typical passive section. The section is 60 inches long, has an inside diameter of 30 inches and an outside diameter of 54 inches. The homogenous fibrous lining is of 4.5 lb/ft³ mineral wool. The construction of the perforated metal interface is shown in the lower sketch in Fig 15.

Figure 16 is a longitudinal cross sectional view of the 36 inch long active section. The lower sketch shows the porous liner sandwiched between two layers of perforated metal. The Owens Corning fiberglass Type 701 was slightly compressed to yield 1 rc (410 mks rayls) flow resistance for the 1 inch thick layer.

The perpendicular cross sectional view of the active section is depicted in Fig 17. The Perpendicular plates divide the active liner into an upstream and downstream half. This is necessary to reduce axial coupling (between upstream loudspeaker and downstream microphone and vice versa). The four axial divider plates, shown in Fig 17 are needed to reduce perpendicular coupling between adjacent active lining quadrants. The 16 actuators were loudspeakers Model 10K 617, manufactured by Focal. The 16 error sensors were Model TMS130A-R Acoustical piezoelectric microphones manufactured by the PCB company.

4.2 Control System Design and Description

The various control configurations were discussed in Section 3. Here we describe only the two SISO feedback control configurations which were used in experimental evaluation of the model-scale augmenter with an active liner section.

The control system used in the quarter-scale augmenter model was implemented as independently operating analog SISO feedback controllers. These SISO controllers were configured in two ways. First the SISO controllers were configured as eight independently operating controllers with the output voltage of two microphones from each quadrant summed and the two loudspeakers in each quadrant driven in parallel as illustrated in the top part of Fig. 18. The second configuration averaged the output voltage from all eight microphones in

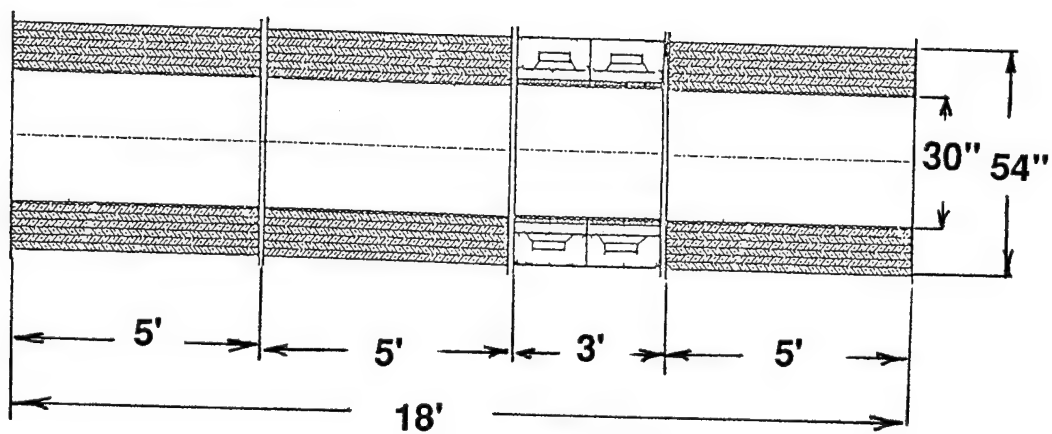
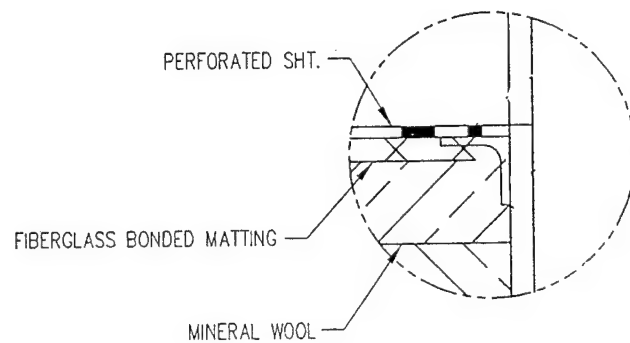
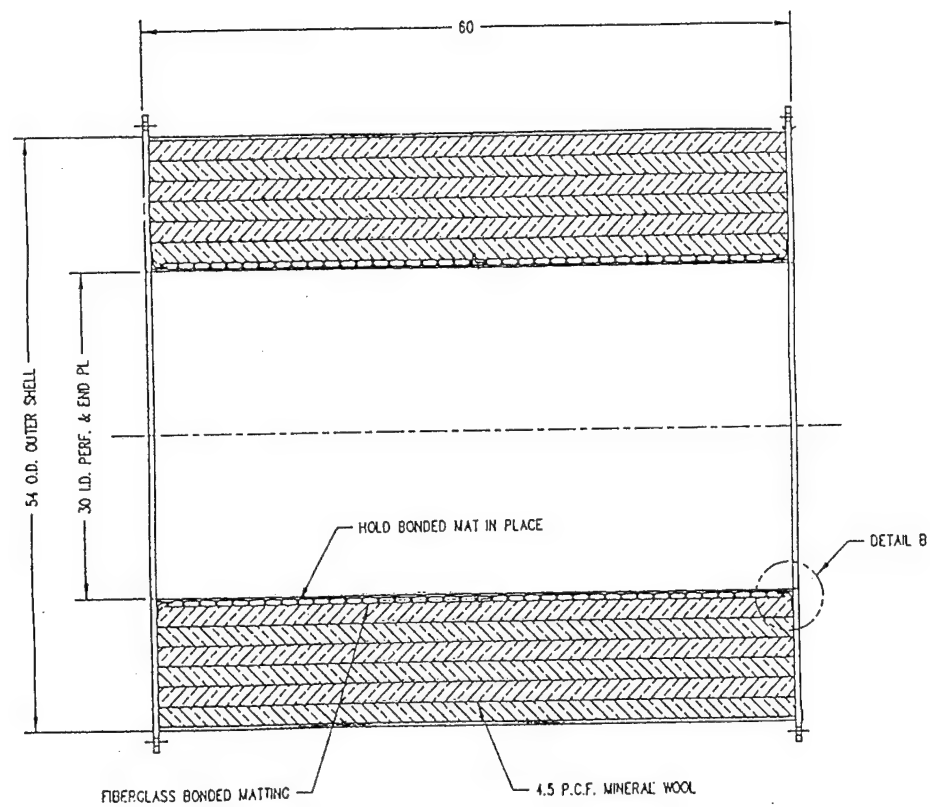


Fig. 14 **Cross Sectional View of the 1:4 Scale Model Augmenter Tube**



DETAIL B

Fig. 15 Longitudinal Cross Sectional View of a Typical Passive Section of the Model-Scale Augmenter Tube

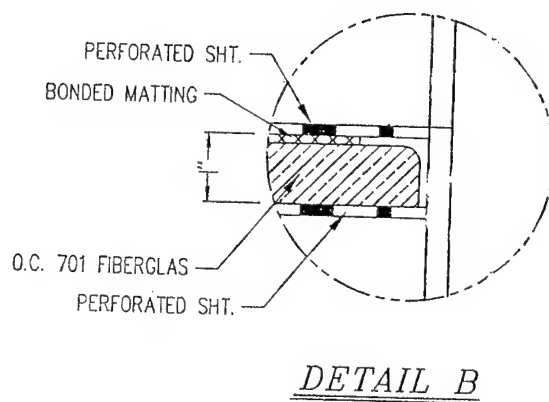
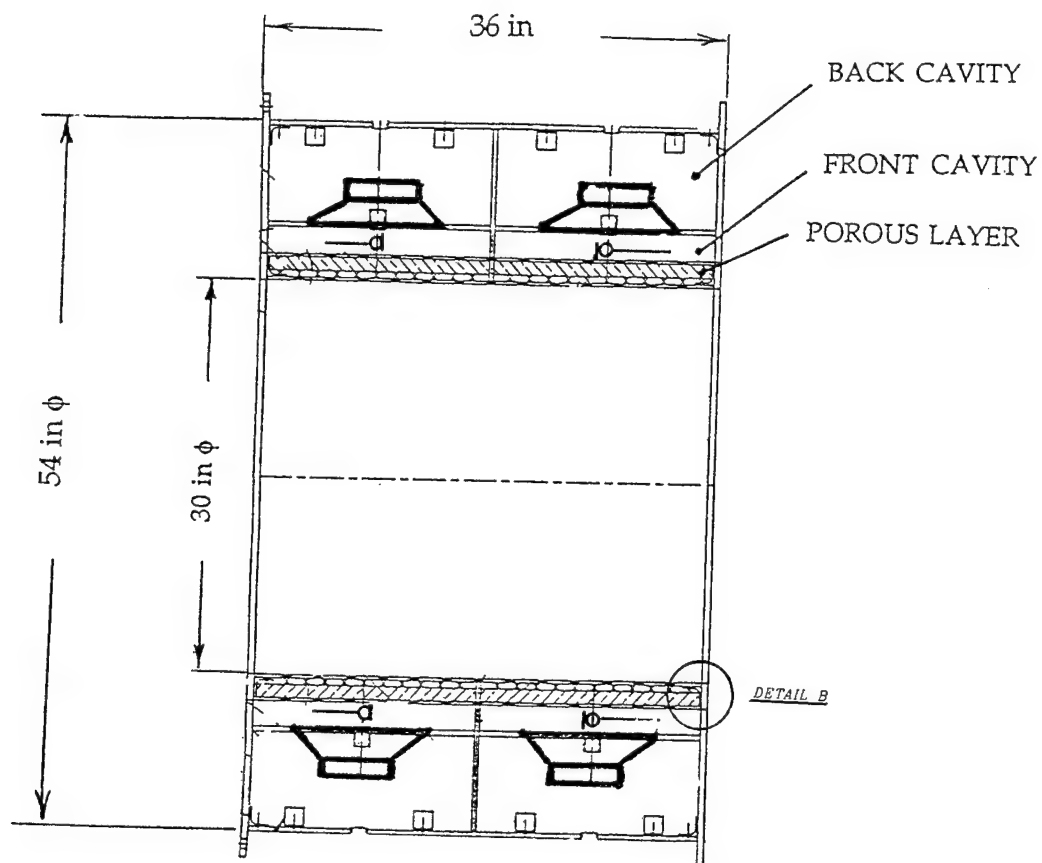


Fig. 16

**Cross Sectional View of the Active Section
of the Model-Scale Augmenter Tube**

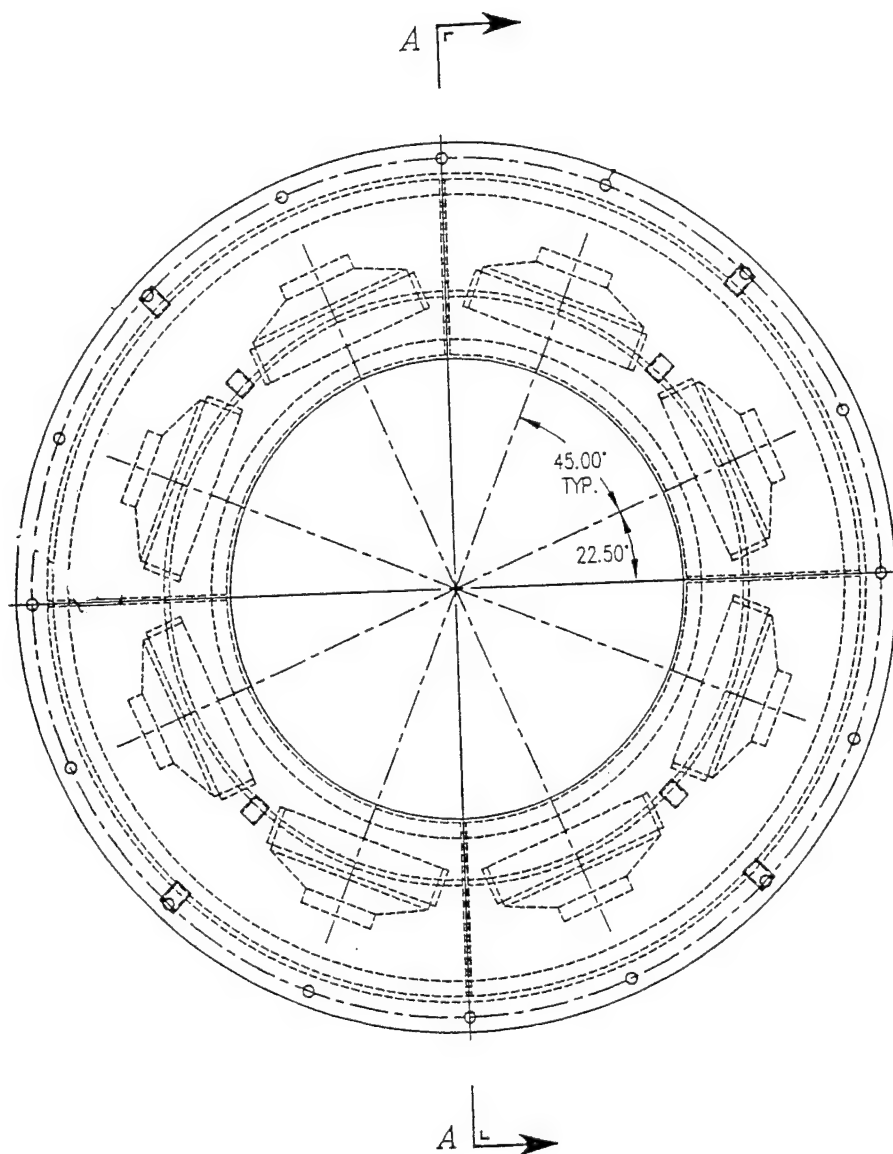


Fig. 17

Perpendicular Cross Sectional View of the
Active Section of the Model-Scale Augmenter

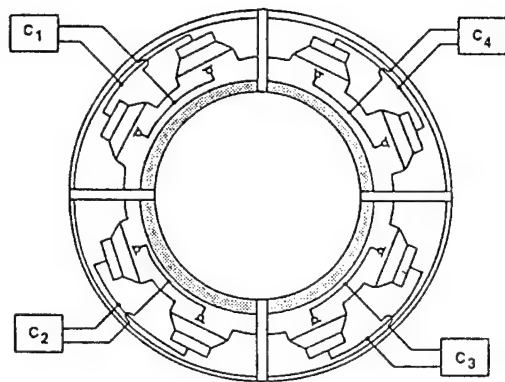
each cross section as shown in the bottom of Fig. 18. The output of the controller drove all eight loudspeakers in the cross section in parallel. These control configurations are shown in Fig 18.

Feedback control was used to keep the entire control system in a local configuration in which the sensing microphone and loudspeaker are contained within a single space in the cavity behind the porous liner. A feedforward control system that requires an upstream and downstream sensor would more complicate the control system design. Because the control system components are in close proximity, the plant transfer function is not expected to vary appreciably; especially in a laboratory environment. Therefore, the controller was implemented on an analog circuit board with fixed filter characteristics.

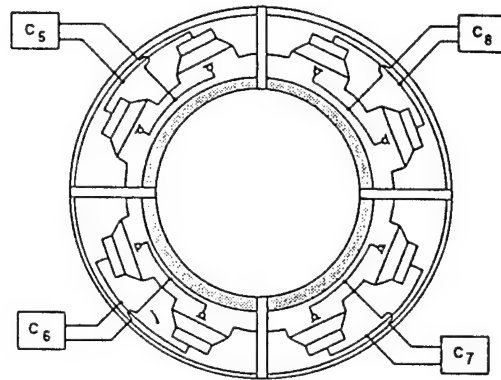
The control board shown in Fig 19 was designed by BBN to provide a flexible design tool for analog control development. The analog control boards were designed as a series of opamps (operational amplifiers) with open sockets on the input and feedback connections. The open sockets can be populated with resistors and capacitors to create various filter characteristics for compensation and regulation. The opamp modules can be cascaded and/or cross connected as needed to create a particular filter characteristic.

The loudspeakers used for the scale model control system were Focal model 10K617 loudspeakers. These loudspeakers were selected because they have a 10 inch diameter, a power handling capacity of 350 watts for continuous noise, a peak displacement of 11 mm, and a free air resonance of 22 Hz. These characteristics assure that this loudspeaker is capable of producing sufficiently large displacement needed to cancel low frequency noise in a relatively compact space. The loudspeakers were powered with a RANE model MA6 six channel amplifier. All the sensors used for the scale model evaluation were PCB Model TMS130A-R Acoustical microphones.

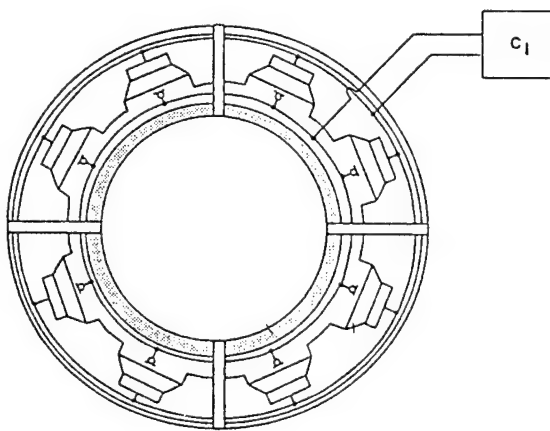
The design of the scale model controller required first measuring the dynamic characteristics of the plant, P , and the development of an inverse model of the plant, G . The inverse of the plant model was then combined with the regulation filter and implemented on the control boards. The controller was designed such that simply changing a few resistors and/or capacitors would modify the frequency and magnitude of the peak attenuation of the regulation filter. The regulation filter was designed to provide peak attenuation between 50 and 60 Hz, rolling off gradually. The attenuation provided by the control filter is shown in Fig. 13. This attenuation is the ratio of the controlled to uncontrolled sound pressure in the cavity behind the resistive layer, as discussed in Section 3.1.



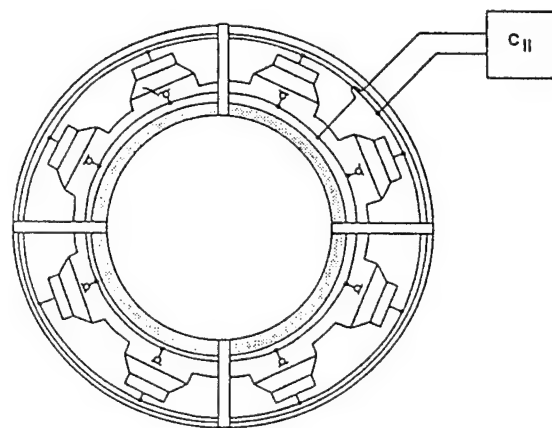
SECTION I
(Upstream)



SECTION II
(Downstream)



SECTION I
(Upstream)



SECTION II
(Downstream)

Figure 18: Active Silencer Section with SISO Feedback Control
Top: 8 Independently Operating Controllers
Bottom: Two Independently Operating Controllers, One for Each of the Upstream and Downstream Sections

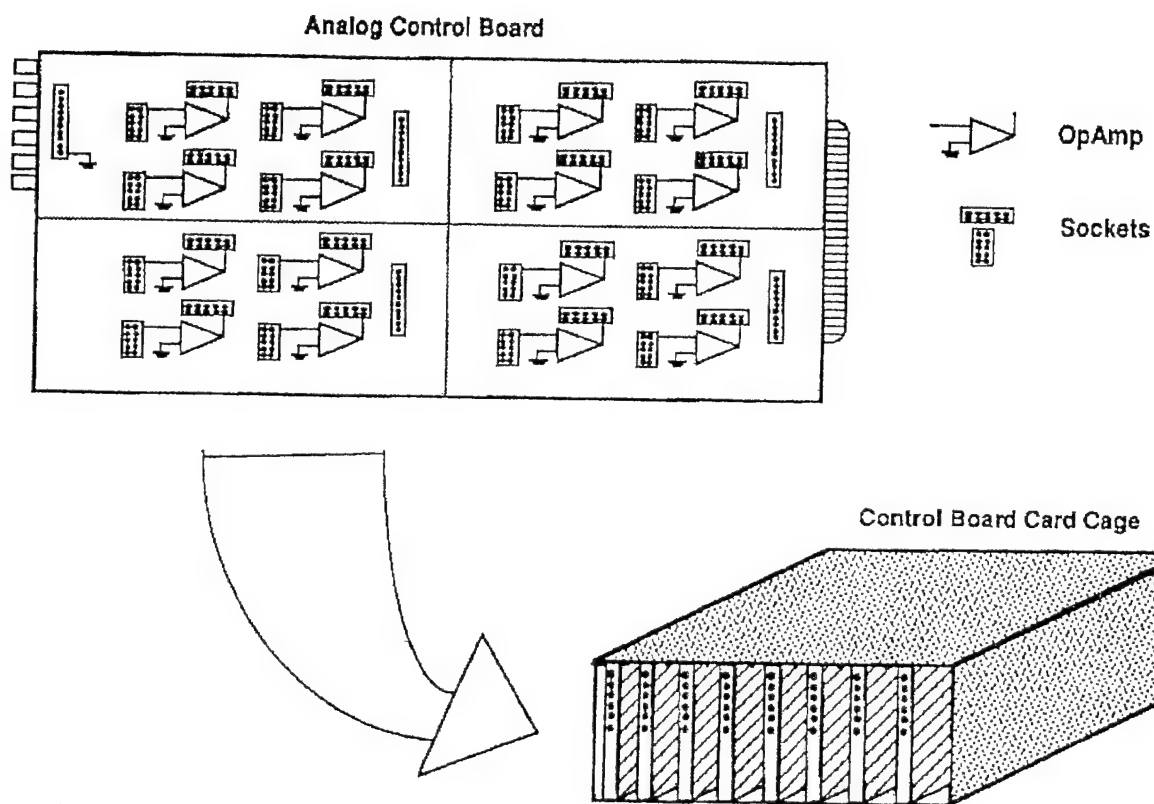


Figure 19: Typical Analog Feedback Control Board and Card Cage

5 EXPERIMENTAL EVALUATION

This section contains information about the

1. Goals of the experimental program;
2. Experimental setup of the model-scale augmenter with active liner section in the BBN acoustic wind tunnel;
3. Preliminary experiments performed;
4. Experimental results obtained without flow; and
5. Experimental results obtained with flow through the augmenter passage.

5.1 Goals of the Experimental Program

The main goals of the experimental program performed in Phase I of this project were to:

1. Prove the feasibility of the active liner concept;
2. Prove the feasibility of employing SISO feedback control for reducing the sound pressure in the front cavity behind the porous layer;
3. Obtain experimental information about the extent of cross coupling and how it limits the efficiency of the active attenuation achievable;
4. Evaluate the effects of flow on the sound attenuation achieved by activating the control system.

5.2 Experimental Setup in the Wind Tunnel

Figure 20 shows the 1:4 scale model augmenter with active section in the BBN acoustic wind tunnel. The model is attached to the discharge nozzle of the wind tunnel. Three 10-inch diameter Type 10K617 Focal loudspeakers, equipped with a capped 12-inch inside diameter pipe-enclosure served as the primary noise source. These "primary" loudspeakers were located in the tunnel discharge nozzle, flush mounted with the upstream end of the model augmenter. During measurements without flow, the three primary loudspeakers were flush mounted on a plywood panel equipped with circular openings in front of the loudspeaker membranes, to allow sound radiation downstream into the model augmenter, while blocking sound propagation in the upstream direction. During measurements with superimposed flow, the blocking plywood panel was removed and the primary loudspeakers were secured to the walls of the discharge nozzle.

Figure 21 shows the location of microphones B7 through B12 placed inside of model augmenter passage to measure the decay of sound pressure with

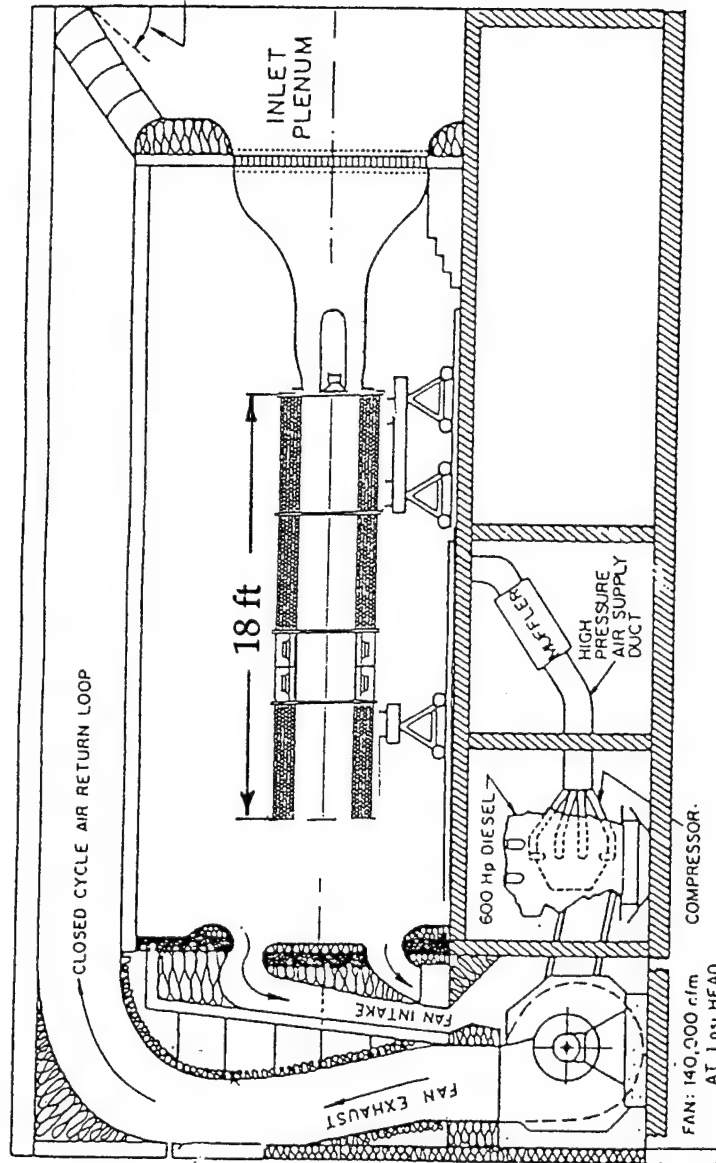


Fig. 20 Model-Scale Augmenter with Active Section Installed in the BBN Acoustic Wind Tunnel for Experimental Evaluation

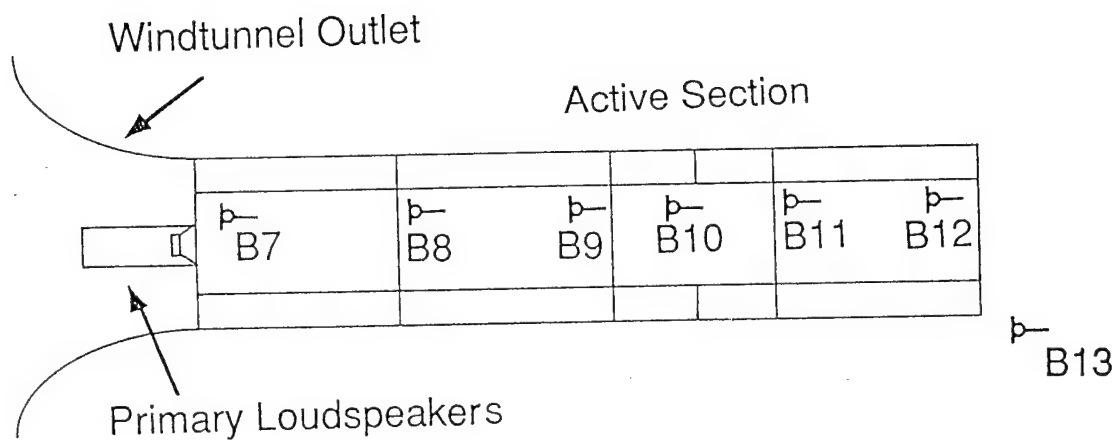


Fig. 21 **Sensor Locations Along the Passage of the Model-Scale Augmenter**

increasing downstream axial distance from the primary loudspeaker noise source. Microphones B7 and B8 were placed at the upstream end of the first and second passive upstream sections respectively. Microphones B9, B10 and B11 were placed at the upstream, center and downstream end of the active section, respectively. Microphone B12 was placed in the downstream end of the model augments passage. Microphone B13 was placed 12 inches downstream and 12 inches radial distance from the downstream end of the model augments passage. For all experiments without flow, microphone B12 was the least affected by flanking via the thin wind tunnel nozzle. Consequently, the sound pressure spectrum measured by microphone B12 with the control system off and on was used to obtain the active attenuation

Figure 22 is a "rolled-out" view of the active section. Positions A1 through A16 designate the position of the error sensing microphones located in front of the 16 canceling loudspeakers. These microphones were fastened to the back side of the porous lining. The second quadrant of the active system was equipped with six additional microphones, B1 through B6, placed in the forward cavity behind the flow resistive liner, to yield information about the spatial extent over which the canceling loudspeakers are effective in substantially reducing the sound pressure in the front cavity.

5.3 Preliminary Experiments

Before commencing with the experimental evaluation of the model scale augments with active liner section, we performed the following preliminary experiments:

1. Checking of acoustic flanking;
2. Setting of the regulation filter bandwidth and feedback gain;
3. Checking linearity limits; and
4. Checking signal/noise ratio.

Checking flanking paths, we found that microphones placed outside of the model augments tube passage (such as B13 in Fig 21) were subject to airborne flanking via the thin wind tunnel nozzle wall. Microphone B12, located at the downstream end of the model-scale augments, was the most appropriate to evaluate the active noise reduction achieved by activating the control system of the active augments section.

The bandwidth of the regulation filter was set to take full advantage of the capabilities of the control system without creating excessive out-of-band amplification. Feedback gain was set to provide substantial reduction of the sound pressure in the front cavity behind the liner and retain sufficient stability reserves.

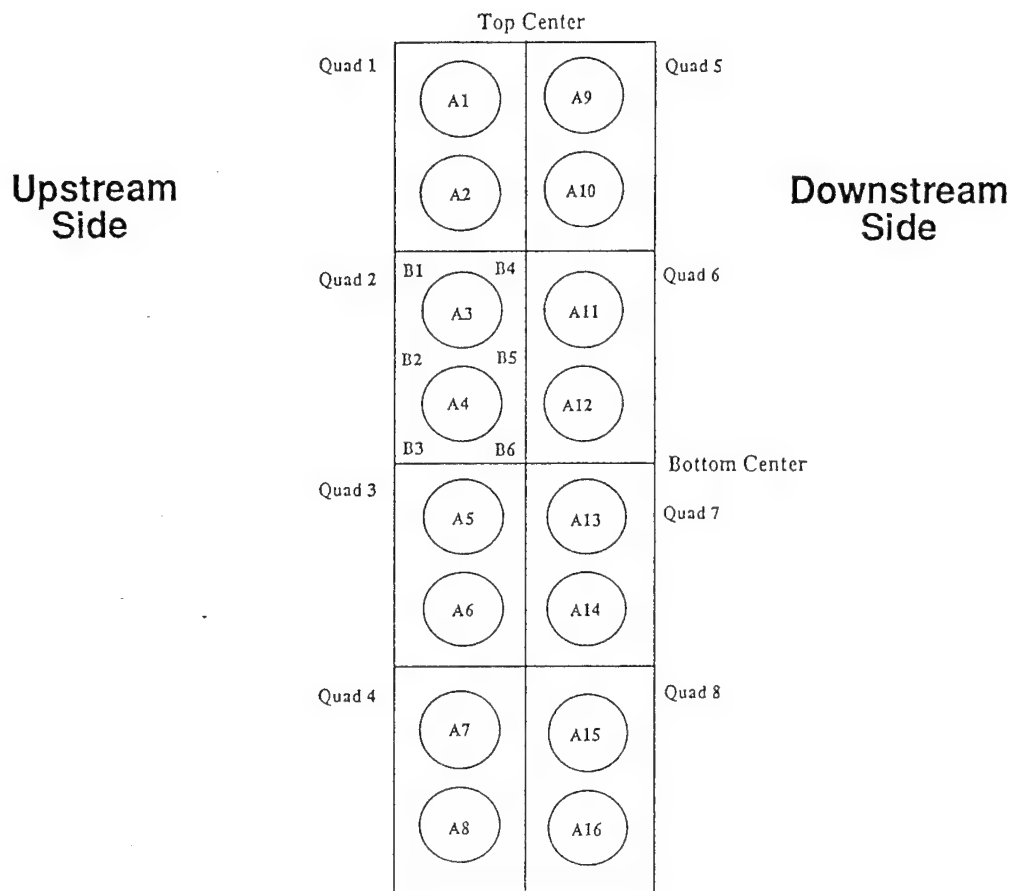


Fig. 22 **Sensor Locations in the Cavities Behind the Porous Liner of the Active Section**

Before proceeding with the experimental evaluation of the acoustic performance of the active section, linearity and signal/noise ratio checks were made.

5.4 Experimental Results without Superimposed Flow

This section contains measured performance curves of the active section in the form of sound pressure reduction behind the liner, active attenuation and measured values of cross coupling between neighboring active quadrants obtained with SISO feedback control of the active augments segment.

Sound Pressure Reduction Behind Porous Liner

As was discussed in Section 2.1, the key idea of the active liner concept is a substantial reduction of the sound pressure in the cavity behind the lining. Fig 23 shows the measured reduction of the sound pressure in the front cavity, obtained by activating the SISO feedback control system. In this and subsequent figures, the measured frequency for the 1/4-scale model is given at the bottom while the corresponding frequencies for a full scale silencer are given at the top. The top curve was obtained when the control was activated only for the specific quadrant measured and the other seven quadrants were uncontrolled. The lower curve in Fig 23 was obtained in the same specific quadrant when not only this but all of the other seven quadrants (each by its own control system) were controlled. The upper curve indicates sound pressure reduction at model scale up to 250 Hz and out-of-band amplification at frequencies above 300 Hz. This corresponds to 62.5 Hz and 75 Hz at full scale. The lower curve shows sound pressure reduction at model scale up to 150 Hz and out-of-band amplification above 250 Hz which corresponds to 37.5 Hz and 62.5 Hz at full scale. The out-of-band amplification for the lower curve exceeds that shown in the upper curve. As discussed subsequently, the loss of control bandwidth and increased out-of-band amplification is a result of cross coupling among the simultaneously controlled active liner quadrants.

Active Attenuation Performance

Active attenuation, obtained by activating the control in the active augments segment, is expected to occur only in the frequency range where the sound pressure in the cavity behind the porous liner is reduced. This is indeed the case as illustrated in Fig 24. The top curve in Fig 24 was obtained when all eight quadrants of the active section were controlled individually as illustrated in the upper sketch of Fig 18. The lower curve was measured when the upstream and downstream halves of the active section were controlled each as a single unit according to the diagram shown in the lower sketch of Fig 18.

Figure 25 shows the active attenuation vs. frequency curve obtained by averaging the narrow band results obtained for SISO feedback control with each

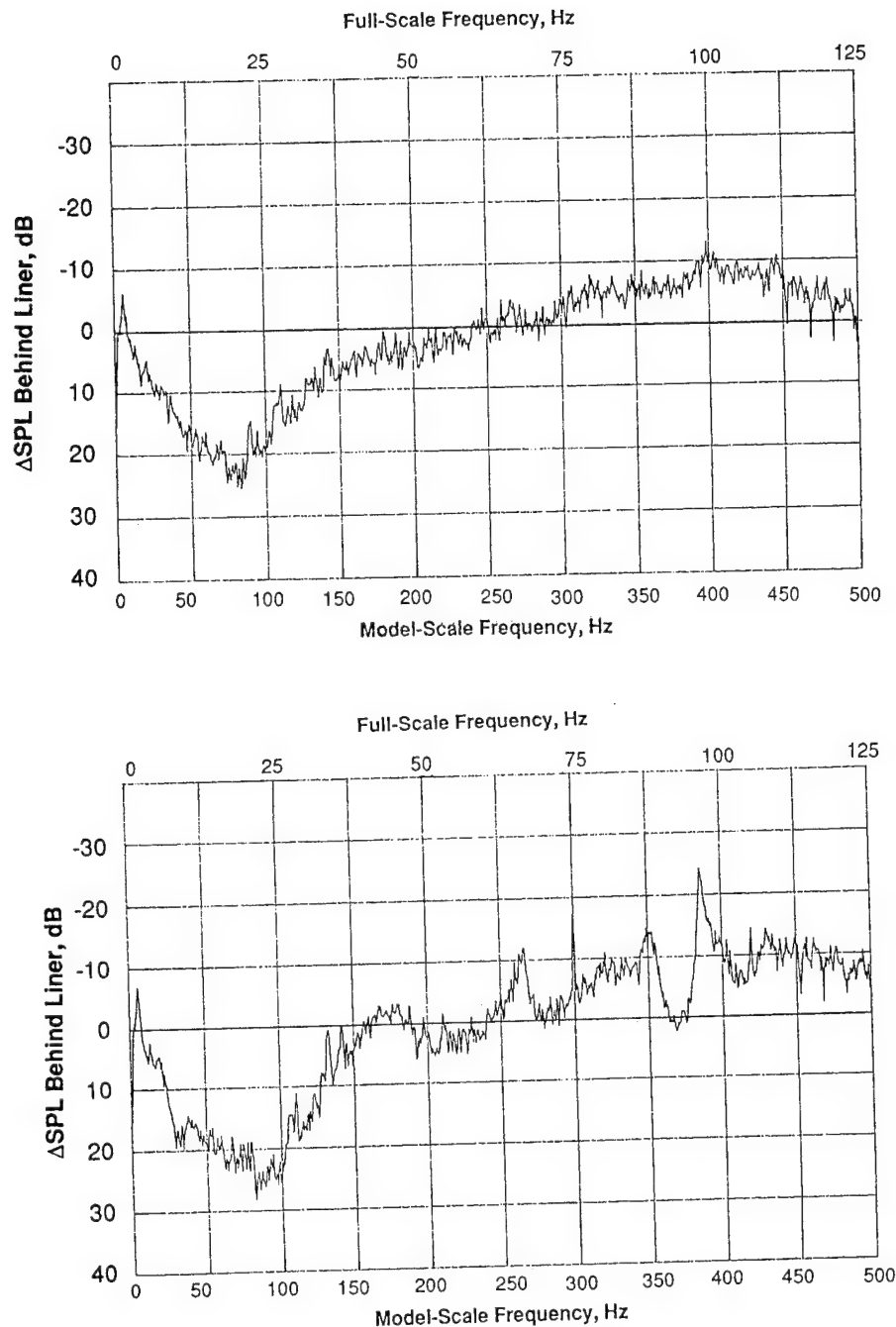


Fig. 23 Measured Reduction of the Sound Pressure in the Cavity Behind the Porous Layer, SISO Feedback Control;
 $\Delta\text{SPL} = \text{SPL (control off)} - \text{SPL (control on)}$

Top: Only Measured Quadrant Controlled
Bottom: All 8 Quadrants Controlled

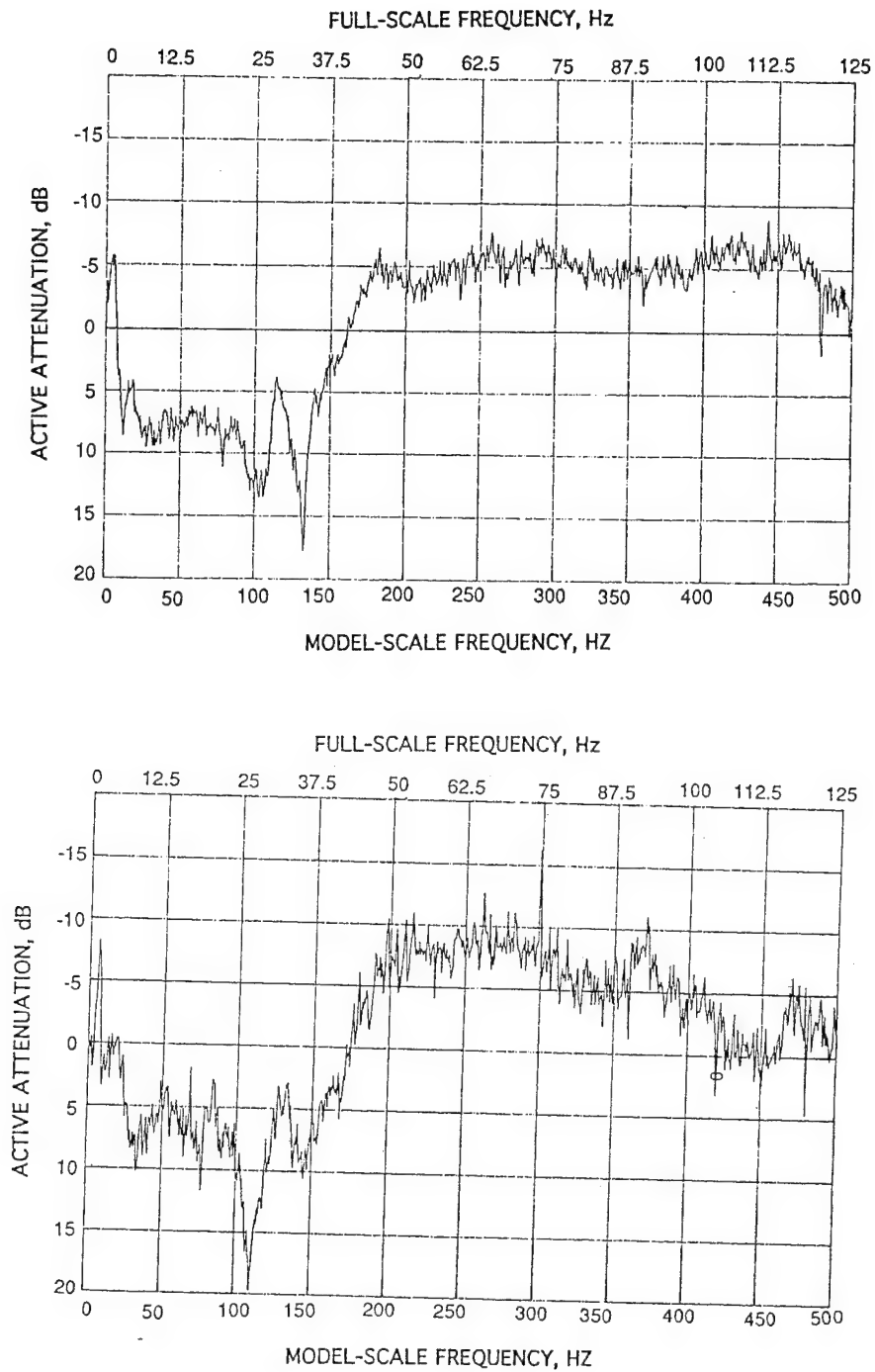
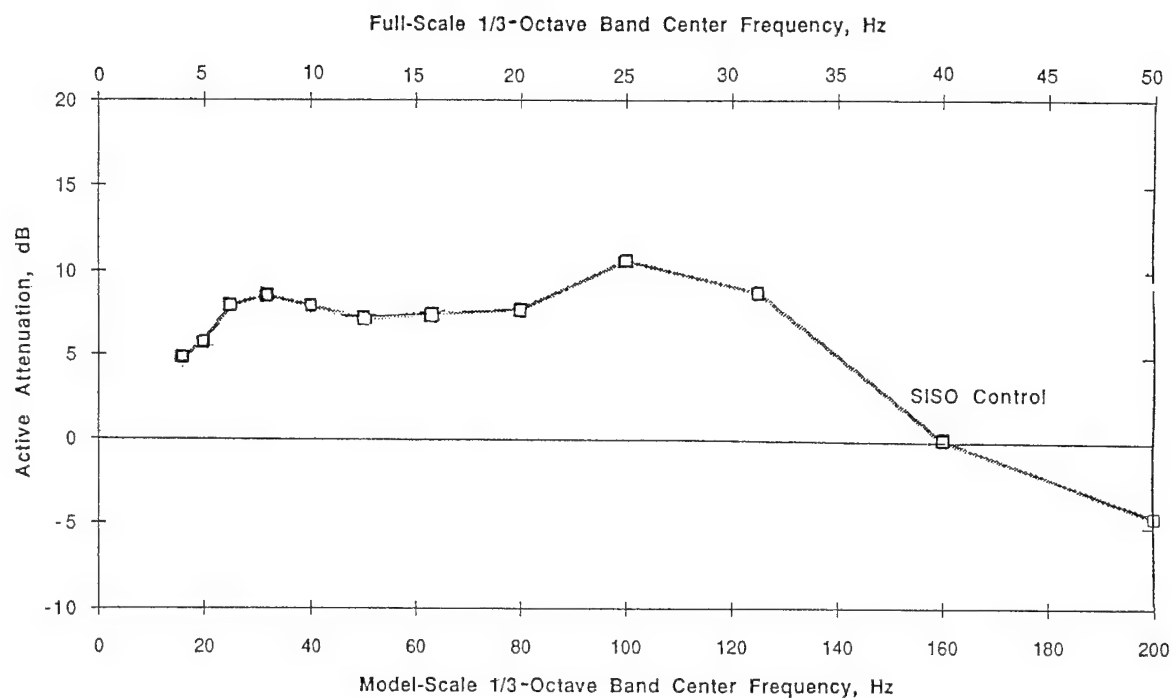


Fig. 24 Active Attenuation Measured with SISO Feedback Control

Top: 8 Quadrants Individually Controlled
Bottom: Upstream and Downstream Halves
Controlled Each as a Single Unit



**Fig. 25 Active Attenuation vs. Frequency in 1/3-Octave Bands;
SISO Feedback Control; 8 Quadrants Individually Controlled**

of the eight quadrants controlled individually, indicating that an active attenuation of about 7.5 dB is obtained in the 16 Hz to 160 Hz model scale frequency range. This corresponds to 4 Hz to 40 Hz at full scale. This is a very high attenuation for a silencer segment that is only 1.2 internal diameter long.*

Cross Coupling

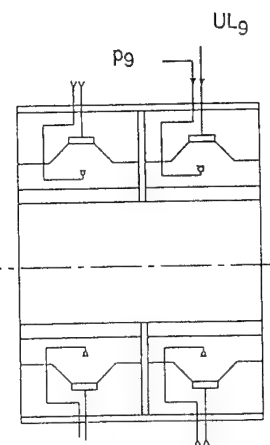
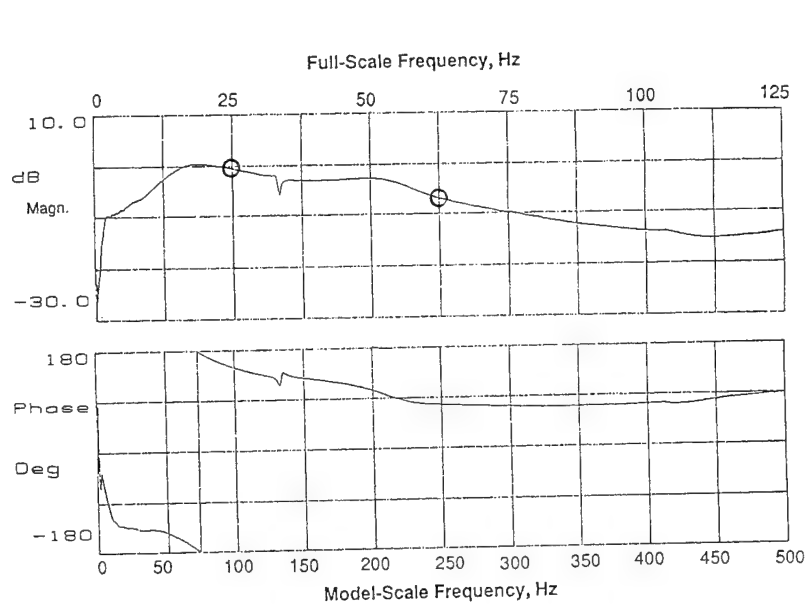
Figure 26 shows a comparison between the direct transfer function microphone A9 voltage/loudspeaker No. 9 voltage (p_9/UL_9) and the cross coupling transfer function microphone A9 voltage/loudspeaker No.1 voltage (p_9/UL_1). The direct transfer function at 100 Hz is about 18 dB higher than the cross coupling transfer function. However, at 300 Hz, the difference is only 8 dB. Since each microphone obtains canceling sound from the nearest loudspeaker only but cross coupling sound from all the other loudspeakers, it is obvious that at 300 Hz (where the difference between direct and a single cross coupling transfer function is only 8 dB) the vector sum of all the cross coupling terms may be as large as the direct coupling term. Consequently, at 300 Hz, the sound pressure cancellation is hindered by the cross coupling. At 100 Hz, (where the difference between direct and a single cross coupling transfer function is 18 dB) the vector sum of all the cross coupling terms is still small compared with the direct coupling, and the sound pressure cancellation is not much affected by cross coupling. Observing the measured sound pressure reduction vs. frequency curves presented in Fig 24 confirms the validity of this argument.

Reducing cross coupling, especially from loudspeakers located upstream of the sensor microphone, is expected to increase the effective bandwidth and magnitude of sound pressure reduction behind the lining and consequently, also the magnitude and bandwidth of achievable active sound attenuation. Cross coupling can be reduced by using a MIMO instead of a SISO control, by separating active sections by a passive section, or by a combination of these two methods.

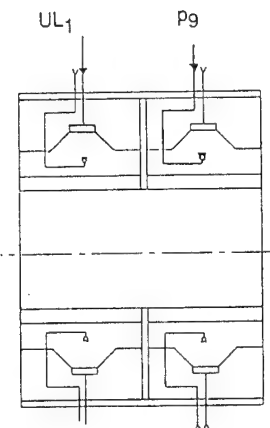
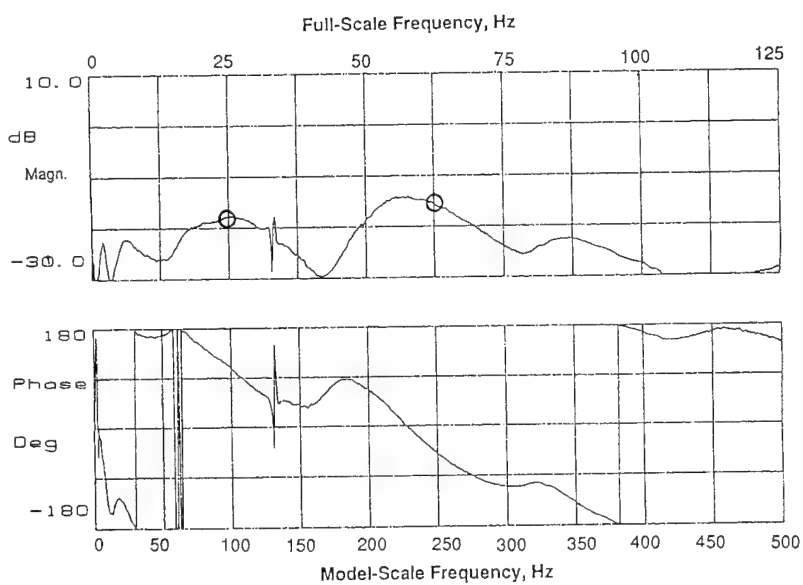
5.5 Experiments with Flow

The effect of air flow (generated by the wind tunnel) in the model augments passage on the acoustic performance of the active liner segment was investigated by measuring the effect of flow indirectly, namely on the reduction of the sound pressure behind the porous liner. A direct measurement of the attenuation utilizing microphone B12 (see Fig 21) was not feasible because the flow-induced noise at this microphone was too high to yield sufficient signal/noise ratio. Microphone B13, which was outside of the flow, was subject to flanking-transmitted noise via the thin wall of the wind tunnel nozzle.

* $L/D_i = 36/30 = 1.2$



p_9/UL_9



p_9/UL_1

Fig. 26 Comparison Between Direct and Cross Coupling

Top: Direct Coupling: p_9/UL_9
 Bottom: Cross Coupling: p_9/UL_1

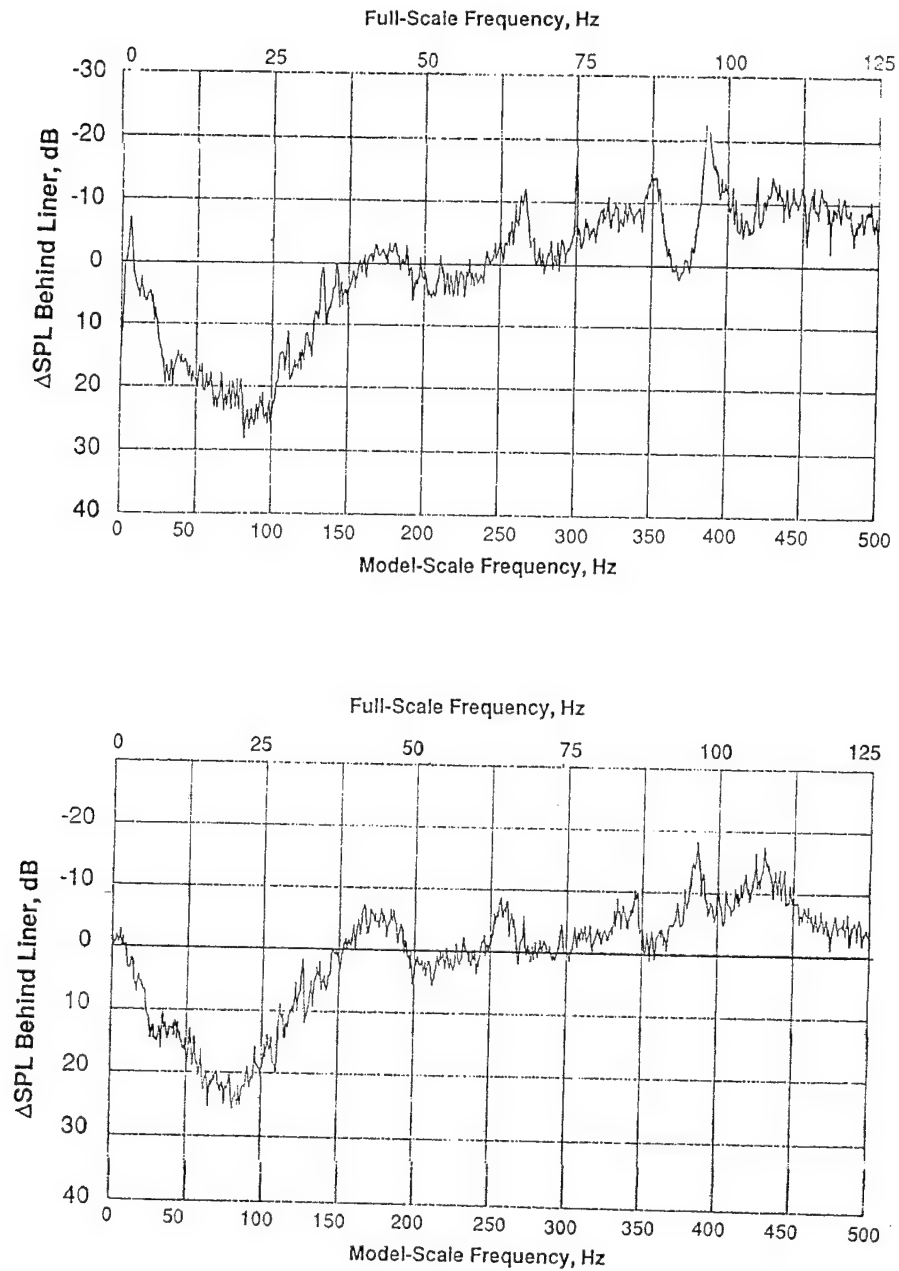


Fig. 27 **Effect of Flow on Sound Pressure Reduction Behind the Porous Liner: SISO Feedback Control**

Top: **No Flow**
Bottom: **2000 ft/min. Flow**

Fig 27 shows the measured effect of flow in the model augmentor passage on the sound pressure reduction in the cavity behind the porous liner. The top curve was obtained without flow and the bottom curve with flow of 2000 ft/min. Comparing the two curves show that the flow had no detrimental effect on the sound pressure reduction. Measurements made in other quadrants of the active section yielded similar results, indicating that the flow (up to the maximum of 2000 ft/min. achievable with the blockage of the primary loudspeakers in the wind tunnel nozzle) had no effect on the cancellation efficiency utilizing the SISO feedback control.

6 FULL SCALE IMPLEMENTATION

Approximate Scaling

Estimates of full scale performance are based on a simple frequency scaling from quarter-scale to full-scale. Strict frequency scaling is a conservative estimate since all the parameters in the control system will not scale. The full scale time delay associated with the actuator and the propagation of sound from the loudspeaker to the microphone will not be four times that of the scale model. These time delays will be equal or less due to positioning of the microphone close to the loudspeaker and use of a higher performance acoustic actuator for full scale implementation. Time delays in a feedback control design limit the frequency range of the controller. The acoustic characteristics of the augmentor will scale by approximately a factor of four.

Performance Goals

The full scale design objective is shown in Fig 28. As explained in the executive summary, the design objective is based on the difference between the sound pressure at 250 ft when an F-16 aircraft operated with after burner in a typical Air Force hush house and the threshold of rattling for a lightweight building. The threshold of rattling for a particular building is dependent on the construction of that building. A one-third octave band level of 80 dB was used as the average threshold of rattling for calculating the design goal. This results in an ambitious design goal based on placing a lightweight building within 250 ft of a hush house exhaust outlet.

Active Control Configurations to Meet Performance Goals

The noise reduction provided by the active silencer is a function of average attenuation of the sound pressure in the cavity behind the porous layer, the flow resistance of the porous layer, and the total surface area of the active section in the augmentor. Assuming the same attenuation as achieved for the scale model,

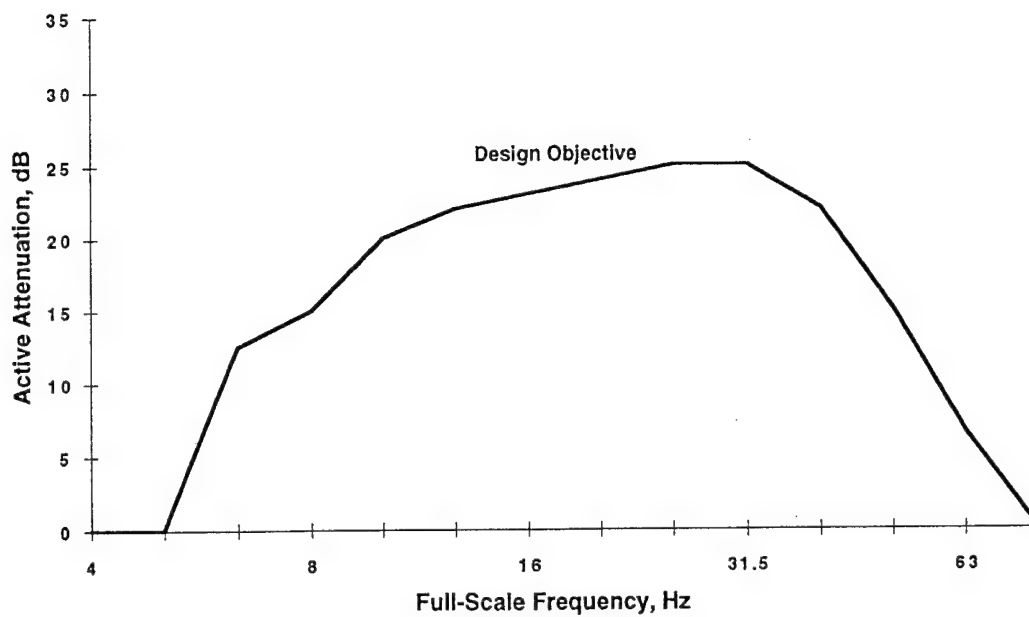


Fig 28: Design Performance Goal for the Full-Scale Active Augmenter Silencer to Preclude Rattling of Lightweight Building Structures at 250 ft.

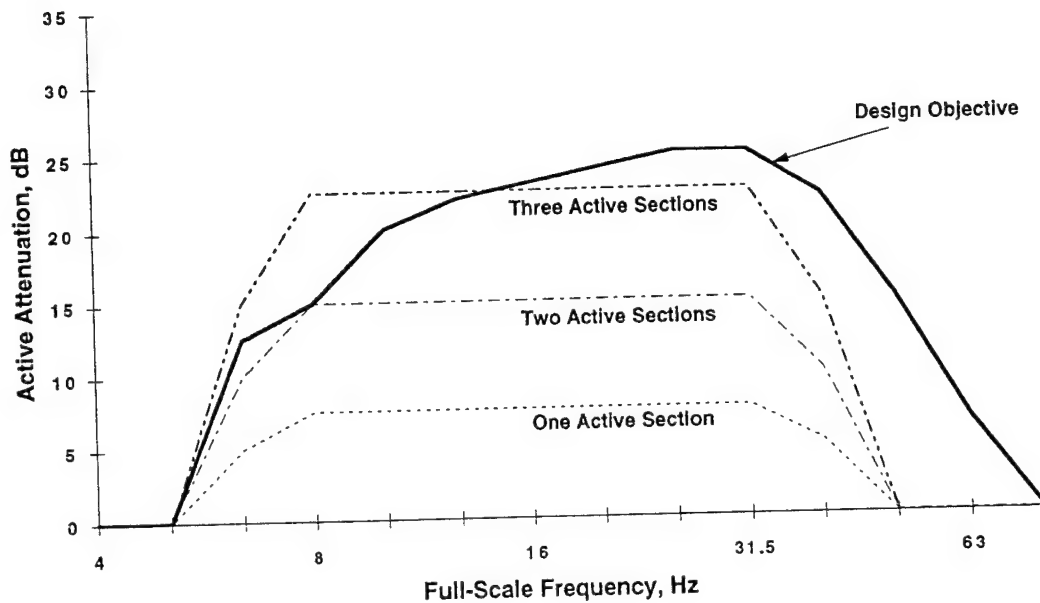


Fig 29: Full-Scale Active Augmenter Silencer Configurations to Meet Design Goals; Liner Flow Resistance 1 pc

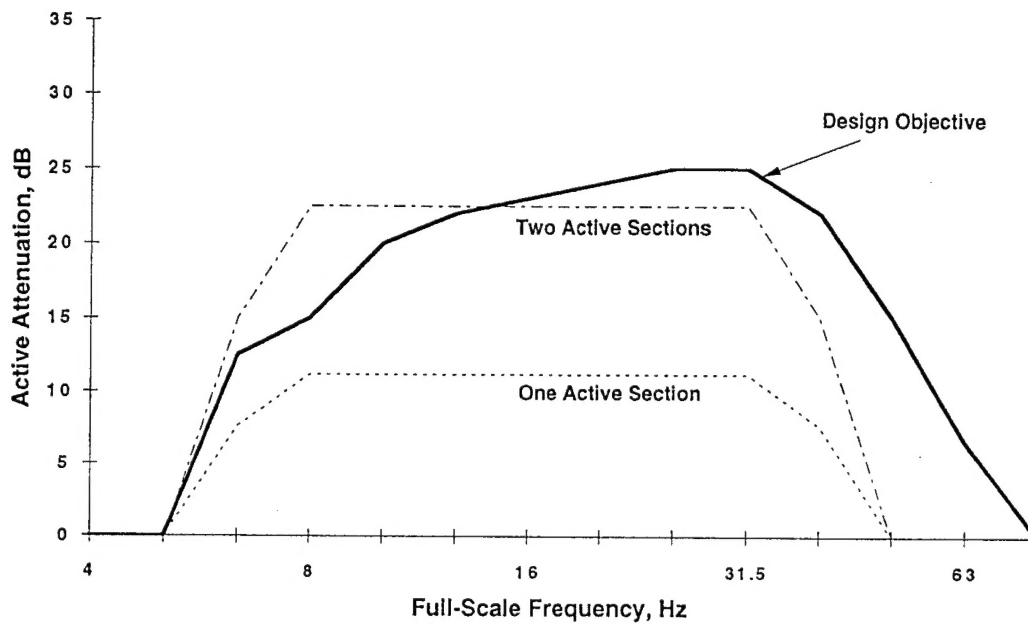


Fig 30 Full-Scale Active Augmenter Silencer Configurations to Meet Design Goals; Liner Flow Resistance $0.5 \rho c$

Figures 29 and 30 show the expected attenuation for varying flow resistance and number of active sections. Each active section is assumed to be twelve feet long with a ten foot inside diameter. The use of a porous layer with lower flow resistance yields higher attenuation. However, the lower flow resistance requires a higher actuator displacement and provides less thermal insulation. An optimum liner flow resistance can be determined from measurements on a full scale augmentor.

The use of additional active sections will provide additional noise reduction proportional to the total surface area of the active sections. If one active section provides 10 dB of noise reduction then two sections will provide approximately 20 dB of noise reduction. Therefore, the number of active sections used for a particular augmentor can correspond to the amount of noise reduction required for that site.

Risk Assessment

Risk for this project has been defined as the risk associated with the transition from a laboratory experiment to full-scale implementation. The basic concept and several implementation issues have been evaluated during the quarter-scale laboratory experiments. However, certain issues cannot be resolved easily with laboratory experiments and require full-scale measurements. To our knowledge, the required full-scale information is not available because there has not been a need for these specific measurements in the past.

The risk areas, the risk assessment and the action needed to resolve the risk area are listed in Table 2. The highest risks in a full-scale implementation are associated with the severe environment in which the control system must function. The control must perform in an environment of hot, turbulent exhaust gases moving at a high velocity.

The high flow rate and the mixing of the hot jet with the surrounding cooling air in the augmentor results in significant turbulence at the surface of the liner. The control system must be capable of discriminating between the convected turbulent pressure fluctuations and the propagating sound waves. A spatial average of the signal of many microphones will provide increased sensitivity to the propagating plane sound waves while averaging out the slower moving turbulent pressure fluctuations. An upstream reference sensor which is both spatially and directionally sensitive is also a possible solution to the turbulent noise problem.

The high temperatures in which the control system must operate are also a concern. However, an actuator designed using high temperature materials and/or a cooling mechanism for the actuator can be developed. As the engine operation shifts into afterburner, a pressure transient results.

A rapid change in static pressure can be accounted for in the actuator and microphone design provided that an accurate measure of the static pressure change is obtained at full scale.

The active silencer will only control the noise that is measured by the control microphone. Any noise generated downstream of a particular active section will not be attenuated. Therefore, the active section should be placed as far downstream as possible. The generation of noise down the length of the augmenter greatly restricts the use and placement of an upstream reference sensor since it will not measure all the propagating noise which reaches the active section. Noise generated at the lip of the 45° exhaust ramp is not affected by the active section. Passive measures that reduce source strength of this lip noise may have to be implemented to obtain the full benefit of the active liner.

Additional risk areas include the required actuator displacement, noise regeneration, and the effect of caustic gases on the control system. These risk areas need to be considered in designing the control system. However, they are not expected to be difficult in overcoming. As with all the risk areas in Table 2, full scale measurements are needed prior to beginning a full scale design in order to fully quantify the environment in which the active silencer must function.

TABLE 2 RISK ASSESSMENT FOR FULL SCALE IMPLEMENTATION

Risk Area	Risk Assessment	Recommended Action
Discrimination of Turbulence from Sound Pressure	Medium-High	Measure TBL Fluctuations and Sound with Sensor Array at Full Scale
High Temperature	Low-Medium	Measure Temp Full Scale, Collect Information on High Temp Transducers, Consider Cooling Options
Rapid Pressure Rise from Military to Afterburner	Medium	Measure P(t) Transient at Full Scale, Consider Passive Limit Stops on Actuators
Noise Generation Along Length of Augmenter	Medium	Measure Sound at Various Positions in Augmenter at Full Scale
Actuator Displacement Requirements	Low	Measure Sound Pressure at Full Scale
Sound Regeneration at Silencer Outlet	Low	Full Scale Measurements, Analytical Prediction and Reduction Techniques
Caustic Effect of Gases	Low	Identify Composition of Exhaust Gases, Collect Information on Resistant Sensors and Actuators

List of References

1. BBN Proposal P93-LABS-N-012, "An Active Liner System for Jet Engine Exhaust Silencers," submitted to the U.S. Air Force, 7 December 1992.
2. Vér I.L. and D.W. Anderson, "Report on the Infrasound and Vibration Study at Luke Air Force Base, Phoenix, Arizona," BBN Report, Prepared for Nevada Design Resources, Inc., 28 April 1984